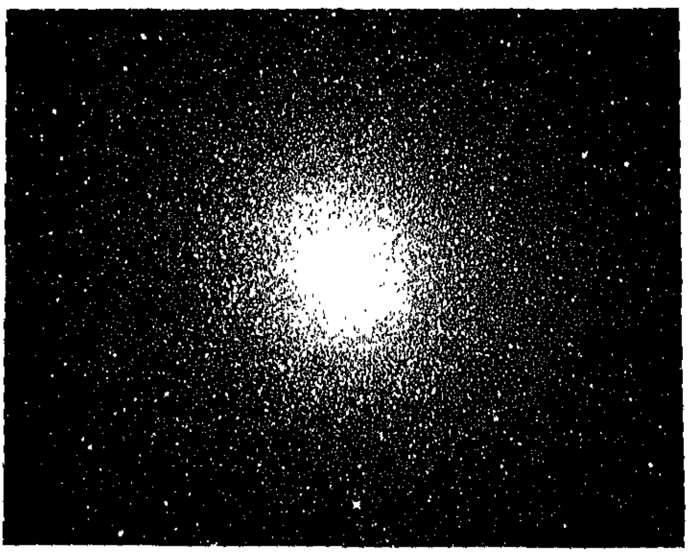
# THE SUN, THE STARS AND THE UNIVERSE

(*a*) The Trifid Nebula (M. 20) in *Sagittarius*.
*Mt. Wilson Observatory.*



(*b*) The Great Star Cluster (M. 13) in *Hercules*.
*Mt. Wilson Observatory*

# THE SUN, THE STARS AND THE UNIVERSE

BY

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*WITH ILLUSTRATIONS*

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TO
MY WIFE

# PREFACE

THIS book is intended for that section of the general public interested in scientific progress. It has been designed to present, in descriptive language and with an historical background, an account of modern astronomical discoveries and of present-day views concerning the characteristics, constitution and organisation of the heavenly bodies. The use of technical language has been avoided as far as possible, and it is hoped that the numerous line-drawings will assist in making clearer the explanations in the text. As the book is systematic in character, some brief reference to certain fundamental matters could hardly be avoided; these have been treated as concisely as possible in Chapter II. During the last decade, the new developments in atomic physics have left their mark on astronomical thought and Chapter VI has been devoted in great part to the simpler aspects of atomic theory. Chapter XV deals with stellar evolution. At the beginning of 1928, three different evolutionary theories were in the field—the theories of Eddington, Jeans and Russell. When this chapter was written it seemed advisable, in a popular book, to devote the available space to a somewhat detailed account of one theory rather than to attempt to produce a condensed description of all three.

I am under deep obligation to the following astronomers for their kind permission to reproduce the beautiful photographs in the book:—Dr. W. S. Adams, Director of Mt. Wilson Observatory (Plates I, VI (*c*), VII, VIII, XIV (*b*), (*c*), XVI, XVIII); Dr. R. G. Aitken, Director of the Lick Observatory (Plates IX, X (*a*), (*b*), XIII); Mr. C. P. Butler, Solar Physics Observatory, Cambridge (Plates VI (*b*), XI (*b*)); Sir F. W. Dyson, Astronomer Royal (Plates III, IV, V); Professor A. S. Eddington, Director of Cambridge Observatory (Plate VI (*a*)); Professor E. B. Frost, Director of the Yerkes Observatory

of the University of Chicago (Plates XV, XIX); Dr. R. T. A. Innes, late Director of the Union Observatory, Johannesburg (Plates XII (*b*), XX); Dr. W. J. S. Lockyer, Director of the Norman Lockyer Observatory (Fig. 1); Dr. J. S. Plaskett, Director of the Dominion Observatory, Victoria, B.C. (Plates II, XVII (*b*)); Dr. H. Shapley, Director of Harvard Observatory (Plate XIV (*a*)); Dr. Max Wolf, Director of Heidelberg Observatory (Plates XI (*a*), XII (*a*), XVII (*a*)).

Lt.-Col. F. J. M. Stratton and Dr. J. A. Carroll have read the manuscript and I thank them for their helpful criticisms and suggestions.

W. M. S.

OBSERVATORY, CAMBRIDGE,
*August* 1928.

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# LIST OF PLATES

# THE SUN, THE STARS AND THE UNIVERSE

## CHAPTER I

### GENERAL ACCOUNT OF THE SOLAR SYSTEM

THE simplest phenomenon of astronomy is one that can be observed every clear day. It is a commonplace of our daily experience that the sun rises above the horizon in the east, climbs higher in the sky until, at noon, it reaches its greatest altitude, thereafter declining towards the western horizon, where eventually it sets. If the night sky is clear, a similar phenomenon is observed as regards the stars. The whole vault of heaven appears to rotate; indeed, the majestic march of the stars across the sky is one of the most glorious spectacles in the whole realm of nature.

The apparent daily movement of the heavenly bodies is a consequence of the rotation of the earth. The earth is approximately a sphere, and we—the observers, situated on its surface—are not directly conscious of this rotational movement; we are not aware that we are being whirled around, for example at Cambridge, at the amazing speed of 10½ miles per minute. The reality of the spinning of the earth about an axis can be demonstrated experimentally without any reference to the heavenly bodies; the discovery of the earth's rotation by hypothetical scientists inhabiting the caverns of the earth, in which the light of the sun and the glories of the night sky are unknown, might be regarded as one well within their powers. Let the reader imagine himself standing at the centre of a turn-table, such as is used for reversing locomotives. If he fixes his attention on distant objects, the uniform and smooth rotation of the turn-table will produce the sensation that it is his surroundings that are moving round uniformly. Let him now turn his attention to the platform on which he

stands, and he will observe that the direction in which it is being rotated is opposite to that in which the external objects *appeared* to him to move. So it is with the earth. In the northern hemisphere, the direction in which the celestial sphere—the imaginary dome on which the stars appear to be situated—appears to rotate is indicated thus: east towards

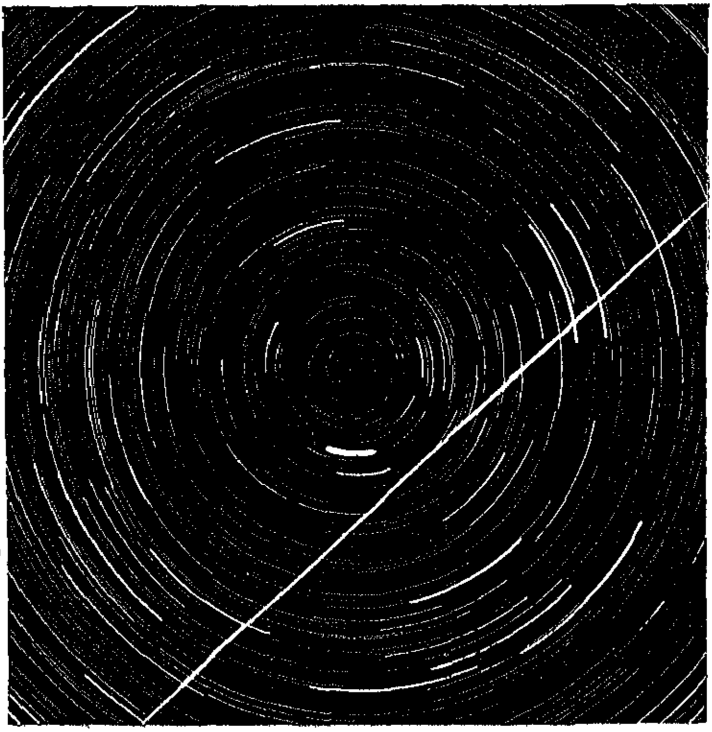


FIG. 1.—STAR TRAILS.
(The bright line is due to a brilliant meteor flashing across the sky.)

south towards west. This rotation is merely apparent—it is the earth that spins, and the direction of spin is opposite to that just stated.

In the northern sky there is one bright star which, even to the careful watcher, betrays hardly a sign of movement, for it seems to occupy the same position in the sky hour after hour. This is Polaris, or the north-pole star, and the direction between

the earth and this star is approximately the direction of the earth's axis of spin. Actually, it is found on more careful examination that Polaris shares in the general apparent rotation of the celestial sphere, and that its position in the sky does change slightly from hour to hour. The point on the celestial sphere whose position remains unaffected by the rotation of the earth is called the north pole of the celestial sphere; a straight line drawn through the centre of the earth in the direction specified by this point cuts the earth's surface in the north pole and south pole of the earth.

Figure 1 is a reproduction from an actual photograph taken on a moonless night with an ordinary camera, fixed in position and pointed accurately towards the north pole of the sky. The arcs of circles are the tracks on the photographic plate made by the brighter stars near the pole during an exposure of about three hours—the figure is thus an illustration of the apparent rotation of the celestial sphere. (The bright arc near the centre is due to Polaris.)

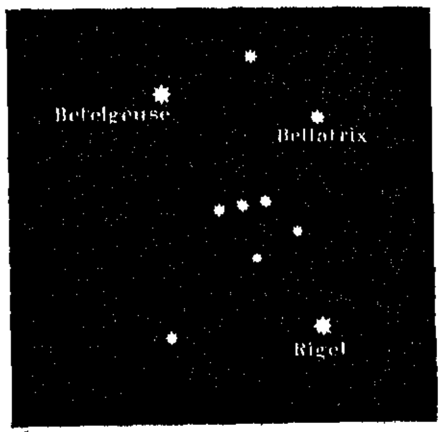


FIG. 2.—PRINCIPAL STARS IN THE CONSTELLATION OF ORION.

The reader is familiar with the general appearance of the night sky and with the fact that the brighter stars appear generally to be arranged on the celestial sphere in indefinite groups or constellations. He is also familiar with the cloudy girdle of the Milky Way, which the telescope reveals as a vast aggregation of faint stars. If he watches the heavens night after night and year after year, he will be unable—with the naked eye—to detect any change in the configuration of the constellations or in their positions with reference to the Milky Way. The constellation of Orion (Figure 2) is the same to-day as it was yesterday, and as it will be to-morrow. The heavens appear unchanged and unchanging, and the stars themselves

might, with justification, be described as "fixed." We now know that the stars are not "fixed," and that the configurations of the constellations are not quite unchanging, but the changes are generally so minute that it is only with the aid of powerful instruments or after the lapse of many years that they can be detected at all. In the early chapters of this book we shall disregard the minute changes alluded to and consider the system of stars as a fixed background, against which the movements of our nearest celestial neighbours—the Moon, Sun, and Planets—may be traced and measured.

Next to the sun, the moon is the heavenly body most familiar to us. On a clear night, let us note its position rela-

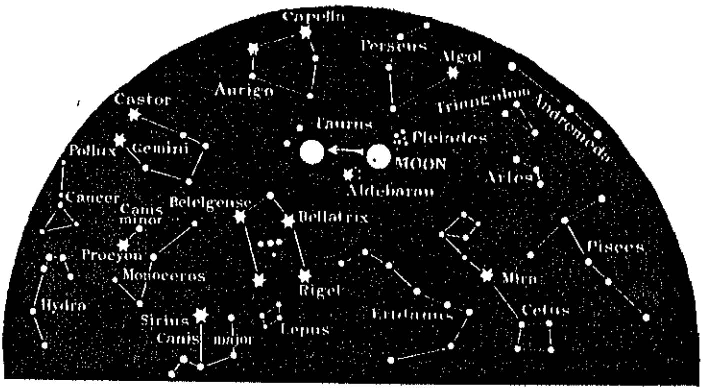



FIG. 3.—POSITION OF MOON AMONGST THE STARS ON TWO CONSECUTIVE NIGHTS.

tively to several neighbouring bright stars near the time of full moon. On the following evening it will be evident that the moon has moved, in the interval, considerably eastwards amongst the stars. On the next evening it will be found still further eastwards with respect to the background of stars, and so on from day to day. Actually, the apparent motion of the moon amongst the stars is so rapid that observations made at intervals of an hour are sufficient to reveal it easily to the naked eye. Figure 3 shows the position of the moon on two consecutive nights; it is based on the simple observations such as we have just described. If the observations are continued sufficiently long, it will be found that

the moon describes a path around the celestial sphere, completing a circuit of the stars in about twenty-seven and one-third days. The interpretation of a series of simple observations of this kind is that the moon moves around the earth in an orbit which, from further considerations, is found to be nearly circular. It will be shown later how the distance of the moon from the earth is determined; it will be sufficient for the present to state that this distance is on the average about 240,000 miles. Also, the diameter of the moon is 2200 miles, which is rather more than a quarter of the earth's diameter. It has already been stated that the earth is approximately a sphere; actually it is found that the earth is somewhat flattened towards the poles, the polar diameter being 7900 miles and the equatorial diameter (*i.e.* a diameter perpendicular to the polar diameter) being 7926 miles.

The moon is said to *revolve* in an orbit around the earth, and the period of revolution with reference to the stars is, on the average, twenty-seven and one-third days. The reader's attention is called to the distinction between rotation and revolution; *rotation* is the spinning of a body about an axis, *revolution* is the motion of one body around another body.

It has been stated earlier that the appearance of the starry heavens is unchanging from day to day. A qualification, which we shall now consider, was omitted intentionally so as not to confuse the issues. Everyone has observed, on occasions, fairly low down in the western sky an hour or so after sunset a brilliant object which is not a star according to our definitions, for, like the moon, it is continually altering its position—as can be easily verified from observations on two or more consecutive evenings—as viewed against the stellar background. It is the planet Venus—a wanderer, as distinct from a fixed star. The brilliant and ruddy object familiar in the winter sky of the northern hemisphere in 1926–1927 is, likewise, a wanderer; it is the planet Mars. To the unaided vision of an observant watcher of the heavens, a planet such as Mars differs from the stars in three particulars: firstly, there are its easily-observed wanderings among the stars; secondly, it shines with a steady light as contrasted with the twinkling of the stars; thirdly, its brightness, from day to day or week by week, is not constant, but slowly altering. In Figure 4 is shown the track of

Mars among the stars between August 1, 1928, and May 1, 1929).

*To the ancients*, five planets were known, viz. Mercury, Venus, Mars, Jupiter, and Saturn. Greek philosophy explained the intricate and puzzling movements of the planets amongst the stars (such as is illustrated in Figure 4) by an elaborate hypothesis to which every advance in observation necessitated further complications. In its final development this was the Ptolemaic theory of the sun and planets. It postulated that the earth was fixed, and the centre of the universe, and that

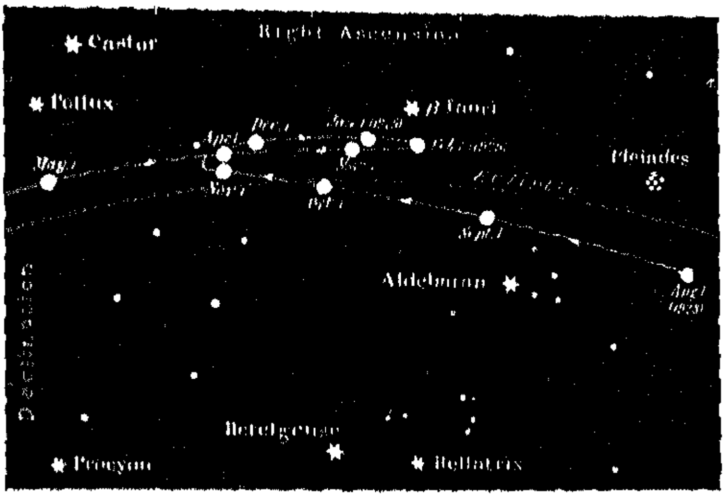



FIG. 4. PATH OF MARS AMONGST THE STARS BETWEEN AUGUST 1, 1928, AND MAY 1, 1929.

the sun and planets and the stars revolved around the earth according to elaborate geometrical devices. This geocentric theory of the universe, supported as it was by the authority of Aristotle, was the creed of nearly every philosopher for over 2000 years, and it really received its death-blow only as the result of the revelations of the newly-invented telescope in 1609 and 1610. The revolution in Greek and mediæval conceptions of cosmogony was begun by the Polish monk, Nicolaus Copernicus, in whose book, published in 1543—*De Revolutionibus Orbium Cœlestium* (On the revolution of the celestial bodies)—was sketched the theory of the sun and planets, known as the

Copernican theory, which is to-day the basis of planetary astronomy. Briefly, Copernicus ascribed the apparent daily motions of the heavenly bodies across the sky to the rotation of the earth, regarded the sun as the true centre of the planetary system, each planet revolving about the sun as primary, and supposed the sun and stars to be stationary. Owing to the insignificant status of the earth in this scheme, contemporary religious thought was profoundly disturbed and bitter antagonism to the new doctrine was provoked; the earth was merely one of six planets (then known) which with the others—Mercury, etc.—acknowledged the sway of the sun. Our present-day knowledge emphasises still more strongly the relative insignificance of the earth as a planet. Is not the earth but a dwarf as compared with the giant planets Jupiter, Saturn, Uranus, and Neptune? Does not it lack the majestic satellite-systems of Jupiter and Saturn, and what has it to show to match the unrivalled and marvellous rings of Saturn? The discovery by Galileo, in 1610, of the four moons of Jupiter established, more than anything else, the Copernican conception as a reliable scientific hypothesis. Here, in being, was a miniature system resembling the greater solar system; here were bodies, actually capable of being observed, revolving about their primary, Jupiter. The culminating achievement was Newton's great discovery of universal gravitation, by which the motions of the planets around the sun as the great attractive centre were explained.

We now proceed to give a more detailed description of the solar system. The sun itself is the most important member, all the other bodies together contributing only about $\frac{1}{7}$ per cent. of the total mass of the system. The diameter of the sun is 865,000 miles, and its volume and mass are approximately each a thousand times greater than the volume and mass of Jupiter, the greatest planet. The major planets in the order of their distances from the sun are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. Uranus was discovered in 1781 by Sir William Herschel, and Neptune, first recognised telescopically in 1846 as a planet, might be described as the offspring of the mathematical genius of Adams and Le Verrier. In Chapter III we shall recount the oft-told, but ever wonderful, story of the discovery of Neptune.

Revolving in orbits between those of Mars and Jupiter are a vast number of small planets; at present well over a thousand are known, and every year sees a large addition to the number. These are the minor planets, or asteroids, the first to be discovered being Ceres, in 1801. They vary in diameter from about 10 miles to 480 miles, the latter being the estimated diameter of Ceres.

The strangest and most spectacular members of the solar system are the comets. The orbits of the major and minor planets are in general approximately circular; a comet, however, makes a near approach to the sun and then recedes to far distant parts of the solar system. Its orbit is greatly elongated, so that it escapes observation, except for the brief intervals in which it is in the immediate neighbourhood of the sun.

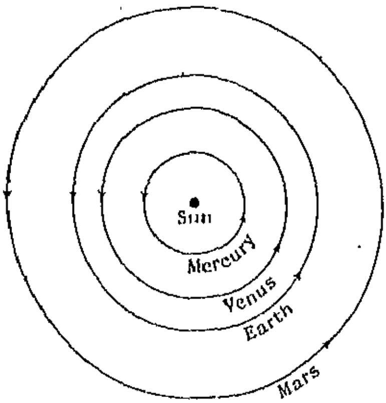


FIG. 5.—ORBITS OF THE INNER PLANETS.

Spectacular also, but transient, are the meteors, which only reveal themselves as they perish in the earth's atmosphere in a streak of glory. They revolve in elongated orbits under the dominating sway of the sun; they are small bodies, their masses ranging from a minute fraction of an ounce to several tons.

It is impossible to represent clearly and distinctly in a single diagram, on a page of this book, the orbits of all the eight major planets, correctly drawn to scale. In Figure 5 are shown the orbits of the four planets nearest the sun, and in Figure 6 the orbits of Mars and of the four most distant planets—in each case drawn roughly to scale.

The fundamental unit of distance in astronomy is the average distance of the earth from the sun; it is found to be, as will be explained in a later chapter, 92,900,000 miles. The most distant planet, Neptune, is separated from the sun by 2,800,000,000 miles, a distance which the human mind finds it well-nigh impossible to envisage. A sailor who has circum-

navigated the earth may be expected to have a more or less definite appreciation of what a journey of 25,000 miles represents in his mind, but the vast distances of the planets and the still vaster distances of the stars are totally beyond the pale of human experience.

It is customary, in non-technical books on astronomy, to express astronomical distances, not in terms of miles, but in terms of the time which light takes to travel from one body to another. It is known, from definite physical experiments, that the velocity of light is 186,000 *miles per second.* This again is a concept which is outside our ordinary experience. A racing motorist who speeds along a track at 127 miles per hour covers 186 feet per second; the velocity of light is 5¼ million times this speed. The unit of distance generally adopted

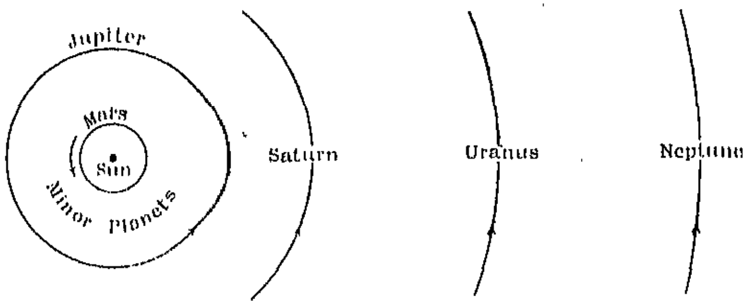



Fig. 6.—Orbits of the Outer Planets.

in this connection is the *light-year,* which is defined to be the distance travelled by light in one year. In a similar way, we may define "light-hour" and "light-minute." Expressing the earth's distance from the sun in terms of light-time, *i.e.* the time taken by light to travel from the sun to the earth, we find that the answer is eight and one-third light-minutes. When we look at the sun we see it, not at the particular instant at which its light enters the eye, but as it was eight and one-third minutes before. In the same way, the distance of Neptune from the sun, expressed in light-time, is a little over four light-hours. Light requires only one and one-third seconds to travel between our nearest neighbour the Moon and the earth.

The extent of the solar system is delimited by the orbit of Neptune. Vast as this is, it sinks into comparative insignificance when we consider the distances of the stars. The distance

of the nearest star from the sun is expressed as four light-years, approximately, in light-time. When we say that this distance is equivalent to 25 million million miles, we are utterly unable to appreciate this stupendous remoteness. On the other hand, we have an instinctive notion of the flight of time, and so the method of reckoning astronomical distances in terms of light-time enables us—in some measure at least—to visualise the vastness of the universe of which we are a part. But it does something more, which it may be well to emphasise here, although the implications have reference to the subjects treated in the later chapters of the book. The method, in fact, suggests the historical side of astronomy, for in the course of an hour an astronomer may gaze upon a variety of objects which may vary in distance from a few light-years to a million light-years; he sees, for example, a star-cluster as it was 500 years ago, another as it was 50,000 years ago, and a nebula as it was a million years ago. Almost in a moment he traverses with giant strides the ocean of time.

The solar system has been thoroughly surveyed by generations of astronomers, and the results of their researches are summarised in the following table; the explanation of how these results are obtained is deferred to succeeding chapters. In the second column are to be found the periods of the revolutions of the planets about the sun. The year is the measure of the period of revolution of the earth around the sun; it is the interval within which the familiar cycle of the seasons runs its course. The planet Mercury, which is nearest the sun, completes its orbital revolution in 88 days, and Neptune, the most distant planet, requires no less than 165 years; thus Neptune has described only about half its orbit since its discovery in 1846.

| Planet. | Period of Revolution in Orbit. | Average Distance of Sun (in astronomical units). | Diameter (in miles). | Speed in Orbit (miles per second). | Number of Satellites. | Mass (in terms of the Earth's Mass). | Density. | Period of Rotation. |
|---|---|---|---|---|---|---|---|---|
| Mercury | 88 days | 0·39 | 3,000 | 23–35 | 0 | 0·04 | 3·8 | 88 d. (?) |
| Venus . | 225 " | 0·72 | 7,000 | 22 | 0 | 0·83 | 5·2 | 225 d. (?) |
| Earth . | 365¼ " | 1·00 | 7,926 | 18½ | 1 | 1·00 | 5·5 | 23h.56m. |
| Mars . | 1·88yr. | 1·52 | 4,200 | 15 | 2 | 0·11 | 3·9 | 24h.37m. |
| Jupiter | 11·86 " | 5·20 | 88,700 | 8 | 9 | 318·4 | 1·3 | 9h.51m. |
| Saturn . | 29·46 " | 9·54 | 75,100 | 6½ | 9 | 95·2 | 0·7 | 10h.14m. |
| Uranus | 84·02 " | 19·19 | 30,900 | 4 | 4 | 14·6 | 1·4 | 10¾ hrs. |
| Neptune | 164·79 " | 30·07 | 33,000 | 3⅓ | 1 | 16·9 | 1·3 | 7h. 50m. |

In the third column are the average distances of the planets from the sun. No planetary orbit is quite circular, and we tabulate simply the average distances from the sun; these distances are expressed in terms of the earth's average distance from the sun—the astronomical unit of distance. Thus, from the table, the distance of Mars from the sun is little more than one and a half times that of the earth, and Neptune's distance from the sun is thirty times the earth's distance from the sun.

In the fourth column are given the approximate diameters of the planets in miles; it will be observed how insignificant the first four planets are in comparison with the outer four great planets.

In the fifth column are found the average speeds, in miles *per second*, of the planets as they describe their orbits round the sun, and it will be noticed, as a general principle, that the nearer a planet is to the sun, the greater is its orbital speed.

In the sixth column is given the number of satellites, or moons, over which the parent planet exercises its local sway.

In the seventh column are to be found the masses of the planets expressed in terms of the earth's mass. Thus, the mass of Mars is about one-ninth of the mass of the earth.

In the eighth column the densities of the planets are tabulated; the density of the earth is given as 5·6, which means that the earth's mass is 5·6 times that of an equal globe of water. The point of interest in the column of densities is that the four small planets have high densities, whereas the four great planets have densities differing little from that of water.

In the last column are found the periods of rotation of the planets, where these are known.

The directions in which the planets, major and minor alike, revolve around the sun show a remarkable uniformity. It is no chance coincidence that these numerous bodies, with not a single exception, revolve in the same direction in their orbits in obedience to the sun's compelling sway; at present, we merely state the fact without seeking or offering an explanation. Also, if we investigate the planes in which the eight major planets revolve around the sun, it will be found that they are nearly the same. It is this circumstance that enables us to picture a simple and yet fairly accurate model

of the sun and the planets. I shall follow Sir John Herschel's description of such a model, modifying it only where it requires correction in the light of modern knowledge.

The sun is represented by a globe, 2 feet in diameter, placed on a level field. The various planets are represented by the objects in the second column below, moving on the surface of the field in approximately circular orbits, whose radii are given in the last column.

| *Planet.* | *Object.* | *Radius of Circle.* |
|---|---|---|
| Mercury . . | Pin's head. | 28 yards. |
| Venus . . . | Pea. | 52 ,, |
| Earth . . . | Pea. | 72 ,, |
| Mars . . . | Large pin's head. | 110 ,, |
| Minor Planets . | Grains of sand and specks of dust. | 120 to 390 yards. |
| Jupiter . . | Medium-sized orange. | 390 yards. |
| Saturn . . | Small orange. | 690 ,, |
| Uranus . . | Small plum. | $\frac{4}{5}$ mile. |
| Neptune . . | Large plum. | $1\frac{1}{5}$ ,, |

On this scale the nearest star would be about 11,000 miles away.

The plane in which the earth revolves around the sun is called the plane of the ecliptic, and we shall suppose our level field to represent this plane. The orbital planes of the major planets differ very little from this plane, but this cannot be asserted of many of the minor planets. Actually, if our model were to be correct, we should have to devise means for making Neptune, for example, move in a plane slightly tilted to the ground, so that Neptune would be represented some 70 yards above the ground at its greatest distance from the plane of the ecliptic.

But even so, the solar system is a remarkably flat system. Imagine a space shaped like a gramophone record, the diameter being roughly thirty times the thickness. If we reduce our model in the proper proportions so that the diameter of Neptune's orbit corresponds to the diameter of the gramophone

record, then the motions of the major and minor planets could all be represented as occurring within this space.

A further uniformity manifested in the solar system is the fact that the directions of revolution of the satellites about their controlling planets is the same (with a small proportion of exceptions) as that in which the planets move around the sun. On Herschel's model, the four great satellites of Jupiter, for example, would be represented by large pin's heads within a few feet of the orange representing Jupiter, and the direction of their motions around Jupiter would be the same as that of the planets around the sun. The exceptions to this rule are the eighth and ninth satellites of Jupiter (the two outermost of Jupiter's satellite system), the outermost satellite of Saturn, the four satellites of Uranus and the satellite of Neptune. It is noteworthy that the exceptions occur at the outermost fringes of the great satellite systems and of the solar system itself.

The largest satellite in the solar system is Titan—the sixth satellite of Saturn—with a diameter of 3550 miles, which is almost exactly half-way between the diameters of the planets Mercury and Mars. At the other extreme are the satellites of Mars, tiny bodies with diameters probably between 10 and 50 miles.

With the exception of our own satellite the moon, the satellites are telescopic objects. To the naked eye of a hypothetical inhabitant of Mars, however, one of the most beautiful objects in the sky would undoubtedly be our own earth-moon system. On favourable occasions the earth would appear a brilliant object, and round it, in the period of twenty-seven and one-third days (according to terrestrial reckoning), would revolve a somewhat less brilliant point, our moon. It is tempting to tarry and speculate on the course of our astronomical history if man had been able to view a similar object in the heavens. It is likely that the progress of theoretical astronomy would not have been delayed for 2000 years; the satellite system of Jupiter, first revealed by Galileo's telescope, would not have been required to illustrate the simple hypothesis of the Copernican doctrines, for a similar phenomenon would have been one of the commonplaces of all time.

According to our model of the solar system, if we represent

the diameter of Neptune's orbit, that is to say, the diameter of the solar system, as $2\frac{1}{2}$ miles, the nearest star would be represented as being 11,000 miles distant. We pause in wonder at the vastness and the marvellous organisation of the solar system, but more remarkable, more astonishing, is the isolation of the solar system in space. The sun is a star—a very ordinary star, as we shall see later—and the distance between our sun and its nearest stellar neighbour may be taken as representative of the distances in general between any two neighbouring stars. The solar system and the stars themselves pursue their lonely ways in the vast abyss of space, separated one from another by stupendous distances which stagger the imagination.

Movement is the life of the universe and the solar system, as a unit, and the stars in general are hurrying about in space, apparently, however, according to no simple plan. A flight of birds may, as a unit, be flying in a definite direction, while individual members may be darting hither and thither, but remaining part of the flight. With reference to the flight as a whole, it is possible to specify the velocity of a particular bird at a given instant. This principle is adopted as regards the motion of the solar system in the universe of stars, and it is found that it is moving at 12 miles per second very nearly in the direction of the bright star Vega, so familiar in our northern skies in autumn, with reference to the aggregate of the stars regarded as a swarm. We shall see later that this cosmic speed of the solar system is about the average for the stars. Let the disc-shaped figure in Figure 7 represent the space within which the planetary motions take place—it corresponds to our gramophone record. The direction in which the solar system as a whole is moving is not in the direction perpendicular to the disc, that is, to the ecliptic, but in a direction, given by the arrow, inclined at some 35° to this perpendicular.

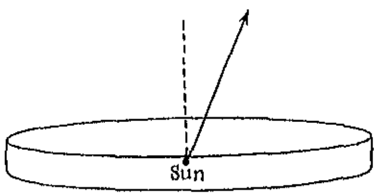



FIG. 7.

# CHAPTER II

## THE CELESTIAL SPHERE

When we look forth at the stars at night they appear to lie on a vast sphere, of which our eye is the centre, called the celestial sphere. The fact is that the eye is able to appreciate, not the distances of the stars from us, but only the angles which they, two by two, subtend at our eye; for example, if two stars appear close together in the sky, the angle between the two straight lines joining our eye to the stars is a small angle; if they appear far apart, the angle is a large angle, and so on. One great and fundamental department of astronomy is concerned primarily with the measurement of angles without any reference to the actual distances of the heavenly bodies from us. Imagine a sphere of which our eye is the centre—the celestial sphere; the line joining our eye to a star will meet the surface of the sphere in a point. We refer to this point as the position of the star on the celestial sphere at a particular instant. We shall attempt to explain briefly certain necessary and fundamental principles.

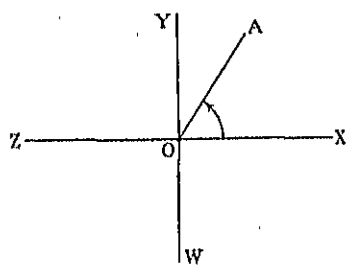



Fig. 8.

Two objects, X and A, are said to subtend at a point O the angle XOA (Figure 8), which represents the amount of rotation of a straight line moving from the position OX to the position OA. If the moving line, starting from OX, passes in succession through OX, OA, OY, OZ, OW and returns to OX, it is said to rotate through an angle of 360 degrees (360°), or four right angles. The angle XOY—a quarter of this complete rotation—is one right angle, which is divided into ninety equal parts, each being one degree (1°). Each degree is divided

into 60 minutes of arc (60′), and each minute of arc is divided into 60 seconds of arc (60″). For example, the angle subtended at the earth by the diameter of the sun or the moon is about 32 minutes of arc (32′).

Many of the fundamental problems of astronomy are concerned with measures of angles, in which a hundredth and even a thousandth part of a second of arc are of the utmost consequence, and it is important to try to obtain some idea of what such minute angles mean. A half-penny, which is one inch in diameter, subtends an angle of 1″ when placed at a distance of 3¼ miles from an observer; many practical problems of astronomy demand an accuracy in the measurement of angles comparable with the measurement of the angle subtended by a half-penny at a distance of several hundreds of miles.

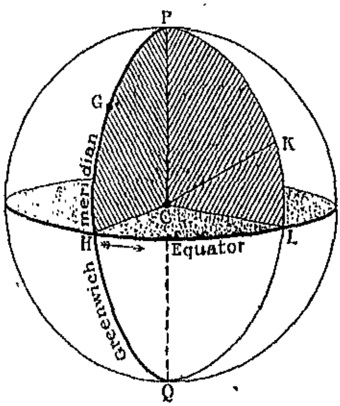



FIG. 9.

*The Earth.*—Positions on the surface of the earth are described in terms of angular measure. In Figure 9, C is the centre of the earth regarded simply as a sphere; QCP is the axis about which it spins. Any plane passing through the centre C cuts the surface in a circle called a great circle. If the plane is at right angles to the axis, the great circle is called the earth's *equator*. Any great circle passing through the poles P and Q is a *meridian*, and that meridian, PGHQ, which passes through the fundamental instrument—the Transit Circle—of Greenwich Observatory is, by agreement, regarded as the principal meridian of the earth from which *longitudes* are measured. The longitude of a place K is defined thus: the meridian through K, *i.e.* PKLQ, cuts the equator in L; the longitude of K is defined to be the angle HCL. Longitudes are measured from the Greenwich meridian eastwards (the direction of the arrow) from 0° to 180°, and westwards from the Greenwich meridian from 0° to 180°. If the longitude of a place is 60° E., its meridian is then definitely specified. The

position of a point on a meridian is defined in terms of *latitude.* In Figure 9 the latitude of K is measured by the angle KCL, and is north latitude if (as in the figure) K is between the equator and the north pole P, and is south latitude if the place is in the other hemisphere.

The positions of the stars on the celestial sphere are described in several systems, in much the same way as that in which places on the earth's surface are described with reference to the two fundamental great circles, the equator and the Greenwich meridian.

(*a*) *Azimuth and Altitude.*—In Figure 10 the celestial sphere is supposed drawn for an observer O in the northern hemisphere (O is the centre of the sphere). Z is the point on the celestial sphere vertically overhead, the vertical direction being defined by a plumb-line. NYS is the great circle whose plane is at right angles to OZ—it is the observer's horizon, dividing the sphere into two hemispheres, of which the upper is the visible hemisphere. The line OP is supposed to be parallel to the earth's axis; P is the north pole of the celestial sphere indicated approximately in the sky by the pole-star. The north point N of the horizon is defined as the intersection of the horizon with the semi-great circle passing through Z and P. The opposite point on the horizon is the south point S. The great circle whose plane is perpendicular to OP is called the celestial equator, or briefly the equator. It intersects the horizon in the east and west points E and W. The position of a heavenly body X on the celestial sphere is referred to the horizon as fundamental plane as follows. Suppose that the great circle drawn through Z and X cuts the horizon in Y, then the position of X at a given moment is completely specified by means of (i) the angle NOY, called the *azimuth*, and (ii) the angle XOY, called the *altitude*. Instead of azimuth, we may

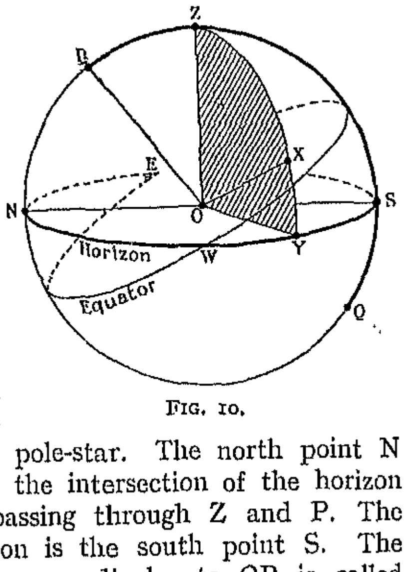


FIG. 10.

use true bearing, which is the angle between ON and OY measured from N through the east point, and instead of altitude we may use the *zenith distance*, which is the angle ZOX.

(*b*) *Hour Angle and Declination.*—In this system the celestial equator is the fundamental great circle. It is a fact of everyday observation that the configuration of a constellation remains apparently constant from day to day, which means that the angle subtended at the earth by any two stars remains constant. In particular, the angle subtended by the pole-star and any other star remains constant. If we suppose, for simplicity, that the pole-star is actually situated at the pole of the celestial sphere, that is to say, at P (Figure 11), then if X is any other star it follows that the angle POX remains constant. As the earth rotates, the star X appears to move across the celestial sphere; hence X must move along the small circle AXC, which is such that wherever X is situated on it the angle POX (called the polar distance) remains unaltered. The altitude of the star is greatest (as can readily be seen from the

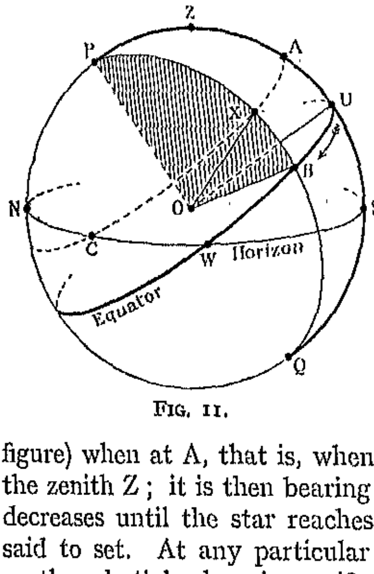



FIG. 11.

figure) when at A, that is, when it is on the meridian through the zenith Z; it is then bearing south, after which its altitude decreases until the star reaches the horizon at C, when it is said to set. At any particular instant the star's position X on the celestial sphere is specified by (*a*) the angle UOB (called the *hour-angle*) measured in the direction indicated by the arrow from the point U on the meridian PZUQ through the zenith (called the observer's meridian) towards the point B, which is the intersection of the equator and the meridian through the position X of the star, and (*b*) the angle XOB, called the star's *declination*. Since POB is 90°, and since also the polar distance POX is constant, it follows that the star's declination is constant. Declinations are measured north or south precisely as for latitudes. Advantage is taken of this

fact of the constancy of declination of a star (as we shall see) in the design of the mounting of astronomical telescopes.

The hour-angle of the star, however, varies. At a particular moment the star is south and at its highest point in the sky (at A in Figure 11). It gradually traverses the heavens towards the west, setting at C; sometime later it rises in the east, climbing upwards until it again bears south at A. The apparent motion is the consequence of the earth's rotation, and the interval between two successive southings of the star—or, as it is termed, between two successive meridian transits of the star—is a measure of the rotation period of the earth. This interval may be described as a star-day; it is about four minutes shorter than the day defined by the sun, as we shall demonstrate later.

(*c*) *Right Ascensions and Declination.*—We have seen that any point on the earth's surface can be specified in terms of latitude and longitude, so that if these are known the point can be accurately found at any subsequent time by making observations and measurements with the appropriate instruments. Thus if it is known, for example, that a ship has been sunk in a particular latitude and longitude, it is fairly easy to locate her on a future occasion. In the hour-angle and declination system of specifying star-positions, only the declination of the star remains constant, whereas the hour-angle is continually increasing during the period of the earth's rotation from 0° to 360°. But the positions of the stars on the celestial sphere may be likened to so many fixed points on the earth's surface—the configuration of the stars remains constant—and so it is possible to define a star's position on the celestial sphere in terms of two fixed angles; one is declination and the other is called right ascension. In Figure 12, suppose V is a star on the equator, then it follows that the angle BOV remains

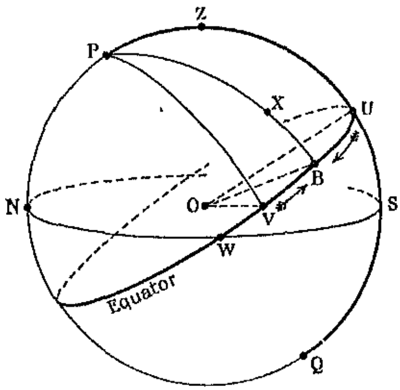



FIG. 12.

constant. This angle corresponds to longitude on the earth, and declination corresponds to latitude. The point V selected in this system is called the vernal equinox, and the angle BOV (corresponding to longitude) is called the *right ascension* of the star X. Right ascension is measured from the vernal equinox V —in the direction indicated by the arrow at V—in degrees from 0° to 360°, or, as is generally the custom, in hours from 0h. to 24h. Just as the position of the sunken wreck is specified by its latitude and longitude, so a star is definitely specified by its right ascension and declination. The hour-angle of V, that is UOV, is called the sidereal time. If we think of V as a star, then the earth's rotation is responsible for the apparent movement of V across the sky. When V is on the meridian the hour-angle of V is 0h., that is, the sidereal time is 0h. When next V returns to the meridian, 24 hours of sidereal time have elapsed. Sidereal clocks keeping sidereal time are an essential part of the equipment of an observatory. From the figure it is seen that the sum of the right ascension and hour-angle of a star is equal to the sidereal time—a rule which enables the hour-angle to be calculated.

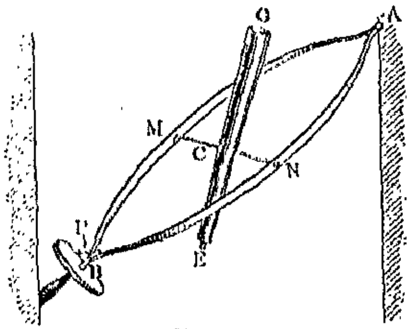



FIG. 13.

The pointing of a telescope to a star whose right ascension and declination are known is a simple procedure. Telescopes are mounted according to the principles illustrated diagramatically in Figure 13. AMBN is a framework which is capable of rotation about the axis BA, the polar axis, which is set parallel to the axis of rotation of the earth. OE is the tube of the telescope, which is capable of rotation about an axis MN fixed, at right angles to the axis BA, in the polar axis frame. The declination of the star being known, and therefore its polar distance, the tube OE is rotated about MN until the angle OCA is equal to the polar distance of the star; OE is then clamped to the axis MN. The right ascension of the star being known and the sidereal time observed from the sidereal clock, the subtraction of the former from the latter gives the

ır-angle of the star, at a given moment. At the base B we ll suppose a circle—the hour-angle circle—graduated from to 24h., with its plane at right angles to the axis BA, which ɔ passes through its centre. A pointer, P, attached to the ne BA enables readings on the hour-angle circle to be de. The mounting, carrying the telescope, is rotated until pointer indicates the hour-angle required. The star is then the field of view of the telescope. But it does not remain g in view as its hour-angle is steadily increasing, and the r consequently passes out of sight unless the whole instrunt is moved by hand or by mechanical means about the s BA. The modern telescope is fitted with an accurate ving mechanism which is responsible for the rotation of the trument about the polar axis at precisely the same rate as t at which the earth rotates, but in the opposite direction; star or stars are thus steadily and accurately held in the d of view. Figure 13—it should be stated again—is intended y to illustrate the general principles of telescopic mounts; the mechanical variations can be studied by the reader he more technical literature.

The vernal equinox—the point V on the celestial equator Figure 12—will now be more completely specified. As the th makes a complete revolution around the sun in the rse of a year, the direction of the earth as viewed from the will make in a year a complete revolution of the celestial ere—of which the sun is the centre—with reference to the rs. But to us on the earth it will appear that it is the sun t makes a yearly revolution among the stars. The plane which this apparent motion of the sun takes place is, of rse, the plane of the ecliptic.[1] This plane is not coincident h the plane of the celestial equator; from observations s found that it is inclined to the latter at an angle of about °. It follows, then, that the direction of the sun from the th lies sometimes on the north-pole side of the celestial ıator and sometimes on the south-pole side; in other words, sun's declination varies throughout the year. This is the

[1] It has already been stated that the orbital planes of the principal planets r very little from one another; consequently, the principal planets are o found in the sky in the neighbourhood of the ecliptic. A narrow zone nding 9° on each side of the ecliptic is called the Zodiac; within it are o seen—under favourable conditions—the sun, the moon and the eight t planets.

cause of the seasons. In northern latitudes the sun is longer above the horizon (that is, the day is longer) when its declination is north than when its declination is south; also, it reaches higher altitudes during the day in the former case than it reaches in the latter. (These statements are easily inferred from a diagram such as Figure 11.)

In Figure 14 we represent the celestial sphere any point on the surface of which indicates the direction of a particular star. We are not concerned at present with the fact of the earth's rotation—the points on the celestial sphere representing the directions of the stars from the earth are now analogous to the fixed points on the surface of the earth. In this figure the celestial equator is shown. The path of the sun, that is the series of points representing the various directions of the sun from the earth with reference to the stars throughout the year, is the great circle DVJSD—the ecliptic. Owing to the inclination of this great circle to the equator the points on the ecliptic between V and J are of declination increasing from 0° at V to $23\frac{1}{2}$° north at J, and so on. We now define the vernal equinox; it is the point V—the point on the equator where the sun's declination changes from south to north (this occurs about March 21). Six months later the sun's declination is again zero, when it changes from north to south declination (this occurs about September 21).

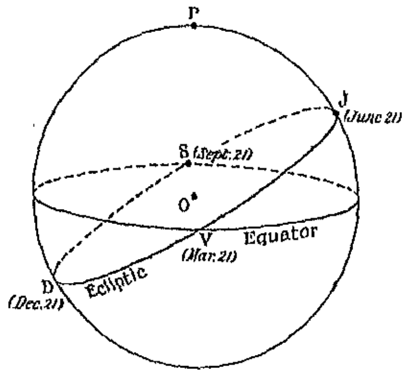



FIG. 14.

If we divide the year into two portions, summer and winter, then astronomically this division corresponds to two periods each of six months, the first between March 21 and September 21 when the sun is north of the equator, and the second between September 21 and March 21 when the sun is south of the equator (this is for northern latitudes). If the earth's axis of rotation had been perpendicular to the plane in which the earth revolves about the sun, varying seasons at any given

place on the earth would be unknown; the sun's declination would be unchangingly zero, and consequently the sun's altitude at noon and the interval between sunrise and sunset would be unvarying also. Winter, spring, summer, and autumn would all be merged into one unending season, and the year would be merely a period of time of interest only to astronomers.

We conclude this chapter by giving a brief explanation of the methods of time-reckoning. The units of time are based on the rotation of the earth. The simplest unit is the star-day, which is the interval between two consecutive passages of a star over any fixed meridian on the earth. This interval represents accurately the period during which the earth makes one complete rotation about its axis. But a star-day is not an observatory unit of time for this reason. The principal point of the celestial equator, namely the vernal equinox—from which the right ascensions of the stars are measured—is not actually a fixed point; it is defined, as we have said, as the intersection of the ecliptic with the celestial equator. But neither of these planes is invariable, although the plane of the ecliptic varies so slowly with reference to the general background of the stars that we may neglect such change conveniently here.

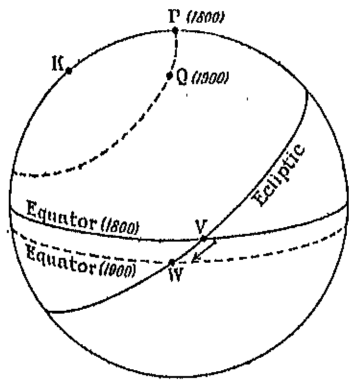


Fig. 15.

It was discovered by Hipparchus in the second century B.C. that the direction of the earth's axis with reference to the stars changes slowly—in other words, that the pole-star of one century is not the pole-star of another. This phenomenon is known as the precession of the equinoxes, later shown mathematically by Newton to result from the attraction of the sun and the moon on the earth, regarded not as a sphere, but as a spheroid. In Figure 15, representing the celestial sphere of stars, P is the pole of the equator, say at 1800, and K is the pole of the ecliptic. After a century, say, the pole of the equator has moved to Q, having described the arc PQ of a small circle, every point of which is at a

constant angular distance KP from K. The point W is the vernal equinox at 1900. The precession of the equinox is then, geometrically, the uniform movement of V along the ecliptic in the direction indicated by the arrow near V, the period of a complete revolution around the ecliptic being nearly 26,000 years. Thus, with reference to the background of the stars, the vernal equinox is a slowly-altering point. The rotation of the earth with respect to the slowly-moving vernal equinox defines the astronomical unit of time, which is called the *sidereal day*.

The civil unit of time is specified in relation to the sun. The interval between two consecutive passages of the sun across any fixed meridian of the earth constitutes a natural unit of time which, however, is not constant from one day to another. If the earth moved uniformly in a circular orbit about the sun in a plane identical with the plane of the earth's equator, this interval would be constant. But we know that the earth's orbit is not quite circular, and that the orbital plane is not the same as the equator; it is a consequence, then, that the natural solar day is not invariable. The average throughout the year is taken to define the mean solar day—the unit of time according to which our ordinary clocks are rated. The mean solar day is about 3m. 56s. of mean time longer than the sidereal day; relatively to the earth, the sun appears to move eastwards amongst the stars, and as the earth's direction of rotation is also eastwards the earth has to rotate a little more than a complete revolution—about 1° more—before the sun is again on the meridian.

## CHAPTER III

### SOME ASPECTS OF EARLY ASTRONOMICAL HISTORY

IN this chapter we shall give a brief account of the chief steps in the progress of astronomical discovery towards the establishment of the modern conception of the solar system.

Some four thousand years ago it was discovered by the Chaldeans that eclipses of the sun (and of the moon) occurred at intervals of about 18 years 11 days—a period known as the *Saros*.[1] This discovery, based on records of eclipses, enabled future eclipses to be predicted with tolerable accuracy. There must have been many apparent failures of the predicted phenomena, for an eclipse of the sun (or of the moon) is visible only from a limited area of the earth's surface; unfavourable meteorological conditions, moreover, would be responsible for further failures to observe the expected phenomenon. But the achievement of establishing then an empirical law was none the less remarkable. We now know that the cause of an eclipse of the sun is the direct interposition of the moon between the earth and the sun; this fact appears to have been first demonstrated by Thales of Miletus (640–546 B.C.), who concluded that the moon was a dark body visible to us only by means of reflected sunlight.

The Greeks were the first to arrive at a definite knowledge of the figure of the earth. The chief observed facts from which they deduced that the earth was spherical (or nearly so) were: (*a*) as they journeyed southwards from Greece to Egypt, the meridian altitude of the southern constellations increased and constellations which were invisible in Greece became visible in more southerly latitudes; (*b*) during an eclipse of the moon the earth's shadow appeared circular. From these observational

[1] The total eclipse of the sun, June 29, 1927, visible in England, had as its two immediate predecessors in the cycle the eclipses of June 17, 1909, and June 6, 1891.

data and others, they concluded that the earth must be a spherical body, or nearly so. Eratosthenes (276–196 B.C.) actually succeeded in determining the radius of the earth as follows. It was noticed that at noon on midsummer day, the sun was vertically above a well at Syene (now Assuan). The meridian zenith distance of the sun on midsummer day at Alexandria was known from observations to be $7\frac{1}{4}°$. Assuming that the distance of Alexandria north of Syene could be obtained in terms of the current unit of length, the radius of the earth was simply deduced from the following geometrical considerations. Assuming for simplicity that Alexandria (A in Figure 16) is exactly north of Syene (S), then at noon on a certain day, the sun is overhead at S, that is, the direction of the sun is SH or CS produced. At A, the direction of the sun is AK, which is practically parallel to SH if the sun's distance from the earth is very great (as we now know it to be) in comparison with the earth's radius, CS. The zenith distance of the sun at A at noon on midsummer day is the angle ZAK, which is equal to the angle ACS. The length of the arc AS being known, the length of CS follows from elementary geometry. In this way the approximate dimensions of the earth were first obtained—one of the earliest triumphs of astronomical measurement.

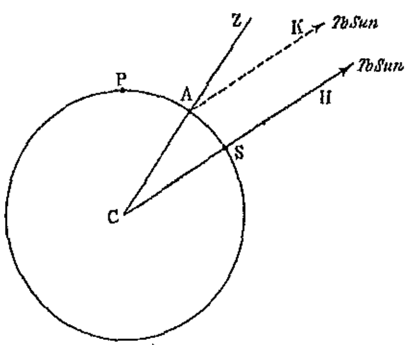


FIG. 16.

One of the characteristic features of Greek astronomy was its persistent attempt to find a satisfying explanation of the structure of the universe. It must be remembered that the instruments of observation were exceedingly crude according to modern standards, and that only the more striking of celestial phenomena came under the notice of the observing astronomer. It seemed natural at first to postulate that the earth was the most important of the heavenly bodies and to regard it as the fixed centre of the visible universe round which revolved the sun and moon and stars. But by the fourth century B.C.

the idea of the distinction between real and apparent motions was grasped: in particular, the daily motions of the heavenly bodies from east to west might be *apparent* only and merely the visible result of the earth's rotation. At this stage Greek genius had progressed a considerable way towards the Copernican conception of the universe. Now a retrograde step was taken. Aristotle (384–322 B.C.)—justly acclaimed one of the greatest philosophers of all time—adopted the suggestion made somewhat earlier by Plato that the motions of the heavenly bodies could be represented by motions on spheres and circles with a fixed earth at the centre. This hypothesis was subjected to mathematical treatment and new-found deviations between the implications of the hypothesis and the results of observation only served to show that the original hypothetical model was

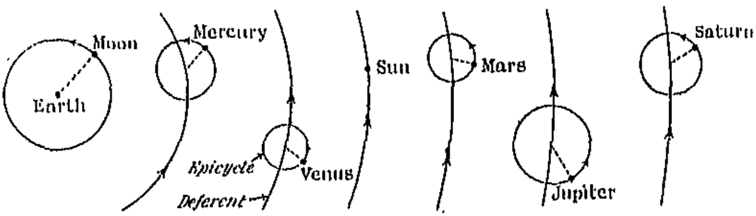



FIG. 17.—THE PTOLEMAIC SYSTEM.

hardly adequate, whereupon new spheres and circles were added to remove the observed inconsistencies. For nearly two thousand years the influence of Aristotle in philosophy and science was dominant, and it is hardly surprising that even Hipparchus, the greatest of the Greek astronomers, fell under the spell of the master-mind. He introduced simplifications into the Aristotelian conception which was further modified by Ptolemy: the Ptolemaic system in its final form survived almost unchallenged for fourteen centuries.

As regards the motions of the members of the solar system, the Ptolemaic plan was briefly as follows. The motion of a planet such as Venus relative to the fixed earth was compounded of a motion round a circle called the *epicycle* (Figure 17), the centre of which travelled along the circumference of a larger circle (shown only by an arc in the figure) called the *deferent*. The sun's motion took place in a simple circular orbit, intermediate in position between the deferents of Venus and Mars.

Simple additional hypotheses intended to explain the apparently complicated motion of a planet (for example, see Figure 4) were made—into which we need hardly enter here. It is sufficient to say that this ingenious scheme was able to explain the general features of planetary motions, but when its predictions were confronted with observations there was usually a discrepancy too considerable to be attributed to any possible errors in the observations.

The one exception among the successors of Aristotle who did not uphold the latter's cosmogonic theories was Aristarchus, who was led to the belief in a rotating earth revolving about the sun, the true centre of the solar system—views that lay dormant for eighteen hundred years.

Before bridging the gap between the Greek era of astronomical and philosophical activity and the dawn of Copernican ideas on a world still perversely impatient of any departure from the pure teaching of Aristotle, we may briefly notice two conjectures—both fully substantiated as soon as Galileo's telescope was pointed to the heavens. The first was that the dull markings on the moon's surface were due to mountains and the shadows which they cast; the second, that the misty girdle of the Milky Way was merely a vast agglomeration of very faint stars apparently densely packed together. The suggestion of the first surmise was that there was at least one heavenly body bearing a strong resemblance to the earth, and the second that the universe of stars was hardly likely to be limited to the few thousand which, individually, were sufficiently bright to be perceptible by the unaided eye.

Nicolaus Copernicus was born at Thorn in Poland in A.D. 1473 and died in 1543. His life-work, the exposition of the solar system according to the views which bear his name, marked the first independent challenge to the infallibility of Greek astronomy, and, in particular, to the Ptolemaic system of the planets. The doctrines of Copernicus rested primarily on clear ideas regarding relative motion, and on this foundation was built up his conception of the solar system with the sun at rest, the earth and the planets revolving in circular orbits around the sun, the earth rotating about an axis, the moon the only body revolving about the earth, and the stars themselves on a great sphere at comparatively remote distances

from the solar system. These ideas of Copernicus were not merely vague conjectures; they were subjected to mathematical analysis and prediction, and the observed phenomena of the planets could be represented with greater success on this system than on the more cumbrous and artificial hypothesis of the Greek school. Although Copernicus had to have recourse to subsidiary systems of epicycles to account for the complete representation of the planetary motions, the great merit of his conception was its comparative simplicity. The new doctrines quickly gained converts amongst the reputed astronomers of the time, and almanacs were published based entirely on Copernican principles. But Copernicanism made little headway against the academic conservatism of the schoolmen and the rugged stubbornness of the theologians. The Church and the Reformers alike denounced his doctrines as incompatible with the teaching of the Bible; the philosophers stood, unmoved, by the principles of Aristotle; at Oxford, Masters and Bachelors were liable to a fine of five shillings for every sin against the pure doctrines of Aristotelian philosophy. Controversy raged unceasingly until the discoveries of Galileo settled, in due course, the victory on the side of Copernicanism and established the fundamental feature of the new system, namely, that the earth is but a planet and, like its fellow planets, revolves around the sun which is the true centre of the solar system.

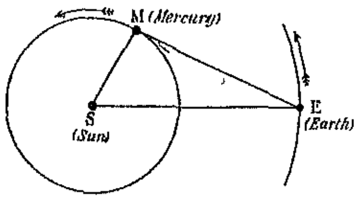


FIG. 18.

One of the notable achievements of Copernicus was the calculation of the distances of the planets from the sun in terms of the earth's distance from the sun as unit (the latter distance is the astronomical unit of distance). For the planets Mercury and Venus, whose orbits were presumed to lie within the orbit of the earth, the principle of measuring the relative distances of, say, Mercury and the earth from the sun was geometrically a simple matter (Figure 18). It consisted in ascertaining by observation the maximum angle subtended at the earth by the sun and Mercury; this clearly occurs when Mercury is at such a point M of its orbit that SME is a right angle. The angle MES being found from observations (the

details need not be described here), the ratio of the distance SM to the distance SE follows by a simple calculation. The distances of the planets whose orbits lie outside the orbit of the earth are found by an analagous method—also in terms of the astronomical unit of distance. The results obtained by Copernicus are remarkably accurate when compared with the modern values.

In any review, however brief, of the history of astronomy the name of Tycho Brahe (1546–1601) must always find an honoured place, for prior to the new era of astronomical discovery about to be ushered in on the invention of the telescope Tycho the Dane stands head and shoulders, as a practical astronomer, above all his predecessors and contemporaries. It was his long series of observations of the planet Mars made, with a care and accuracy hitherto unrivalled, in his magnificent and palatial observatory of Uraniborg (situated on the island of Hveen, in the Sound) that enabled his disciple, John Kepler (1571–1630), to discover the three great empirical laws of planetary motion that bear his name. Tycho's skill and patience were such that his observations of the planets and the stars were not liable to errors exceeding 2 minutes of arc, in those days an achievement of the highest order. Consequently, when Tycho and Kepler noted discrepancies up to 4° or 5° between the observed positions of Mars and the positions predicted in the Copernican almanacs, there was no doubt that the errors made in the observations were unable to account for such significant anomalies, and that the cause lay in the insufficiency of the Copernican system. By extending the number of epicycles, which Copernicus had found it necessary to introduce, and after repeated trials, Kepler arrived at the closest reconciliation between theory and observation hitherto obtained, but still the greatest outstanding discrepancy amounted to some 8 minutes of arc. Most of Kepler's astronomical contemporaries would have remained satisfied with such an achievement, but Kepler's confidence in the observational accuracy of Tycho Brahe left him no option but to start afresh on different lines. And as he himself wrote: "But as the error of 8 minutes could not be neglected, these 8 minutes of arc have alone led the way toward the complete reformation of Astronomy." In the Copernican theory the planetary orbits

were postulated to be circles. Kepler asked: "Is this stipulation necessary, and, if not, what is the curve that will best represent the orbit of Mars round the sun?" After trying several types of curves, he was led to enunciate what is known as Kepler's First Law, namely, that the orbit of a planet around the sun is an ellipse with the sun at a focus. Figure 19 shows an ellipse with its two foci at S and T; the ellipse has this property: if P is any point on the curve, the sum of the two lengths SP and TP is constant and equal to twice the length CA, C being the mid-point of ST. If the sun is supposed to be at S, the planet moves along the curve, being nearest the sun at A (*perihelion*) and furthest at B (*aphelion*). The length CA is called the *semi-major axis* of the orbit.

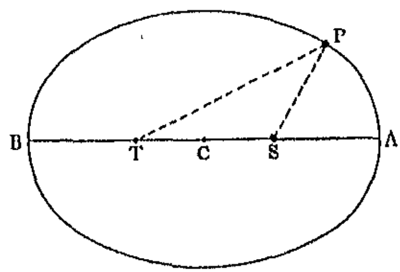


FIG. 19.—THE ELLIPSE.

The apparent simplicity of Kepler's discovery is apt to conceal the enormous mathematical difficulties with which he had to contend. Firstly, a single observation of a planet merely gives its direction at a particular instant with reference to the general background of the stars. Secondly, the observations are made from the earth, which is itself moving along an orbit round the sun. Thirdly, Kepler lacked the ordinary logarithmic aids to calculation with which every schoolboy is familiar.

Kepler next investigated the problem of the speeds with which the planet travelled at various points in its orbit. He found that the planet's angular speed in its orbit was greatest at perihelion and least at aphelion, and eventually he deduced his second law: "The straight line joining the planet to the sun sweeps out equal areas in any two equal intervals of time." Suppose, in Figure 20, the planet is nearest the sun at A on a certain date, and a fortnight later at L. Similarly let M be its position sometime later, and N its position when a fortnight has intervened between M and N. Let U and V be two subsequent positions with a fortnight's interval between them. Then Kepler's second law states that the three shaded areas are all

equal. Now, A is the point on the orbit nearest the sun, and the angle LSA in the figure is clearly greater than the angle MSN; in other words, the angular speed relative to the sun is greatest at perihelion. Similarly, it is least at aphelion, that is at B.

Kepler's third law was a relation involving the periods of revolution of the planets in their orbits and the relative sizes of these orbits. Both these quantities were known with reasonable accuracy in Kepler's time. The third law is: "The ratio of the squares of the periods of revolutions of any two planets (including the earth) around the sun is equal to the ratio of the cubes of the semi-major axes of the orbits." To Kepler this was simply an interesting numerical relation, apparently independent of either of the first two laws. We shall see later that these empirical laws are the consequence of the great universal law of gravitation, the offspring of Newton's genius.

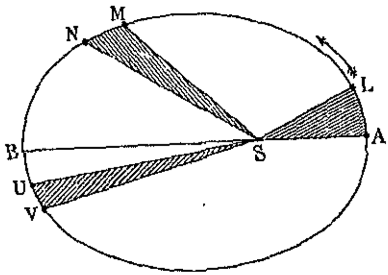


FIG. 20.—TO ILLUSTRATE KEPLER'S LAWS.

Kepler's first two laws were published by him in a book entitled *Commentaries on the Motion of Mars* in 1609, a year memorable for the independent invention of the telescope by Galileo (1564–1642) and the inauguration of a series of astronomical discoveries on a scale of grandeur beyond the wildest dreams of any astronomer before or after him. It is not certain who was the first inventor of the telescope, nor is it certain that Galileo was the first to point the new instrument to the skies; but to Galileo is the undivided credit of grasping the potentialities of the telescope, of appreciating the new and wonderful objects it revealed in the heavens, and of realising the importance of his discoveries in establishing beyond dispute the main features of the Copernican doctrines concerning the sun and planets. The moon was seen to be covered with mountain ranges and craters, and the Milky Way was resolved into innumerable faint stars, thus verifying the two conjectures made two thousand years before—to which reference has been

made. The planet Venus was seen to pass through phases similar in character to what we call the phases of the moon, thus suggesting that Venus was a dark body like the moon, visible only under the illumination of the sun. The sun itself, hitherto believed to be perfect and immaculate, was seen to have several dark markings on its surface, which we now call sun-spots. The arguments of a sceptical cleric of this last discovery make curious reading to us in this scientific age: "I have read Aristotle's writings from end to end many times, and I can assure you that I have nowhere found anything similar to what you describe. Go, my son, and tranquillise yourself; be assured that what you take for spots on the sun are the faults of your glasses or of your eyes." But the discovery which of all gave the shrewdest blow to the blind adherents of Aristotelian philosophy and Ptolemaic astronomy was that of the four great satellites of Jupiter. Here, indeed, was a miniature solar system of which the great Greek sages were ignorant, a system in which satellites revolved in their ordered courses around the parent planet just as the planets themselves were supposed by Copernicus to revolve around the sun. One of the arguments urged by the critics of Copernicus was the very real difficulty of understanding the composite nature of the moon's motion of revolution around the earth combined with the latter's orbital motion around the sun. The satellites of Jupiter provided ocular demonstration of a similar phenomenon.

Scientific scepticism of the new ideas and of the new telescopic revelations could not prevail long against the ever increasing array of evidence in favour of the main contentions of Copernicanism. The Church, on the other hand, maintained with ferocious zeal that the new doctrines were contrary to the Word of God; Galileo was tried before the Inquisition and the first shots were fired in the battle that has almost ceaselessly raged since between organised religion on the one hand and science and the implications of scientific discovery on the other.

In the year that saw the passing of Galileo, Sir Isaac Newton (1643–1727) was born. It is impossible within the compass of a few sentences to give an adequate account of the transcendent genius who left his impress on every department of mathematical and physical science. His rival, Leibnitz, generously and truly

wrote: "Taking mathematics from the beginning of the world to the time Newton lived, what he had done was much the better half." What concerns us here are the steps which led Newton to the great law of universal gravitation, the exposition of which he gave to the world in 1687 in the *Principia*. We have seen that Kepler's three laws were empirical and mutually independent; there was apparently no simple reason why planets should move in their orbits according to these laws. Why should a planet revolve around the sun in an ellipse? Kepler himself was inclined to believe that there was some kind of force which pushed the planet round in its orbit, but such a speculation was barren as well as vague. Newton started from the simple terrestrial phenomenon of a falling body. It had long been realised that when a stone is allowed to fall some force is responsible for the stone's motion in the direction of the centre of the earth. This force evidently operated at the tops of the highest towers and on the summits of the highest mountains. Did it operate as far away as the moon? This question Newton succeeded in answering in the affirmative: the agency that was responsible for the fall of the traditional apple was the same agency that kept the moon revolving around the earth. Suppose a gun is fired horizontally in the direction MT from the top, M, of an eminence at a height NM above a level plain (Figure 21): the bullet will describe a trajectory such as MA. If the velocity of projection is increased, the point of impact on the earth's surface will be (say) at B, further off from N than A. If the velocity be still further increased the trajectory will be lengthened out still more. These are facts which we can regard as obvious deductions from experience. We are led to infer that when the velocity reaches a particular value (about 5 miles per second) the bullet will not strike the earth at all, but will revolve round it in a circle of radius OM, becoming in fact a satellite like the moon. Now, when the

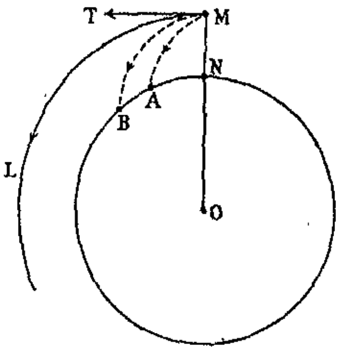


FIG. 21.

bullet is describing the trajectory MA its motion is partly horizontal and partly vertically downwards, the latter part being due to its fall from an altitude NM. So when the bullet is describing the circle of radius OM it is continually falling towards the centre of the earth, as well as moving forward horizontally at each point of the orbit. Consider the situation one second after projection from M with the horizontal velocity of 5 miles per second (Figure 22). The horizontal velocity would take the bullet to Q, MQ being 5 miles, in one second. But it is also falling, so that at the end of one second it will have fallen by a distance QR, R being on the line joining Q to O. Now, if NF is the horizontal line through N meeting OQ in F, the distance NF is practically 5 miles, for NM is very small compared with the radius ON (the altitude NM has been vastly exaggerated in the figure). From the known radius ON or OG of the earth the distance FG can be easily calculated: it is found to be 16 feet. Now, as we have supposed the bullet to be describing a circular orbit of radius OM or OR, it follows that QR is 16 feet. But this is the distance through which a stone will fall from rest in one second at the surface of the earth. The consequence is that, although the bullet is continually falling, it remains at the same distance above the earth's surface, owing to the earth's curvature and the particular velocity of projection which we have assumed. Thus from the known phenomena of falling bodies, a circular orbit of a body moving close to the earth's surface can be adequately explained. Now, what makes a stone fall? We have to invoke the aid of Newton's first law of motion, which is in the nature of a postulate, that a body not acted upon by force will continue in a state of rest or of uniform motion in a straight line; or, conversely, the agency which changes, or tends to change, the state of rest of a body or of its uniform motion in a straight line defines what is called force. Now, a falling body does not move with uniform

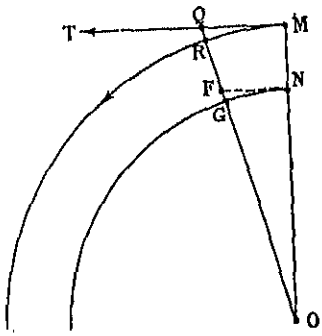


*Fig. 22.*

velocity: it is found by experiment that a stone, dropped from rest, falls 16 feet in the first second and 48 feet in the next second. Therefore a "force" is acting on it which we may describe as a pull. This is a quite definite result so far as motion at the surface of the earth is concerned, and we can explain the circular orbit of the bullet by virtue of this force continually acting on it in a direction always pointing towards the centre of the earth.

Now let us consider the moon's orbit around the earth. The same principles apply, but what is the relation of the force which keeps the moon in its orbit and prevents its flying off at a tangent, to the force at the surface of the earth which makes a stone fall? Newton found, from the known dimensions of the moon's orbit, that the two forces were in inverse proportion to the squares of the radii of the moon's orbit and of the earth. The moon being at a distance from the earth's centre equivalent to 60 radii of the earth, the force at the moon is $\frac{1}{3600}$ of the force at the surface of the earth.

Are there similar forces, obeying the same "inverse square law," which would explain the movements of the planets around the sun? Could the new law of force account for the observed features of planetary motion summarised in the three empirical laws of Kepler? Newton showed that a planet under the action of a force always directed towards the sun and depending only on the planet's distance from the sun would move according to Kepler's second law; that is, the line joining the sun and planet would sweep out equal areas in equal times. With the inverse square law, Newton then succeeded in establishing the general form of orbit—according to circumstances, it could be an ellipse or a hyperbola with the sun at a focus, or a parabola—thus verifying Kepler's first law, which dealt only with motion in an ellipse, and demonstrating further that other forms of orbits were possible under the same law of force. A further deduction of the inverse square law led to the relation between the dimensions of the planetary orbits and the periods of revolution around the sun, which is mathematically expressed in Kepler's third law. Thus Newton succeeded in finding one simple rule—an attractive force directed towards the sun and varying inversely as the square of the planet's distance from the sun—which could

account completely for the planetary movements. What is the nature of this attractive force? Newton suggested that it was fundamentally a property of matter, and stated his great law of universal gravitation: "Every particle of matter in the universe attracts every other particle with a force varying directly as the product of their masses and inversely as the square of the distance that separates them." We are all familiar with the idea of weight; the weight of a book is simply the force with which the earth attracts the book. The ratio of the weight of a book to the weight of a cricket ball is, according to the law of universal gravitation, equivalent to the ratio of the mass (that is, the quantity of matter) of the book to the mass of the cricket ball. But that is not all. The individual particles of matter of which the earth is composed attract the individual particles of matter of which the book is composed, and it follows equally from Newton's generalisation that every particle of the book attracts every particle of the earth. Newton established the theorem that the attraction of all the particles of a sphere of matter (uniform throughout, or in uniform layers) on a particle exterior to the sphere was equivalent to the attraction on the particle of a mass equal to the mass of the sphere and concentrated at its centre. The heavenly bodies are approximately spherical, so that we need here suppose that, as far as gravitation is concerned, their masses are concentrated at their centres. The law of gravitation applied to the motion of, say, Venus around the sun is then expressed as follows: the force with which the sun attracts Venus is proportional to the product of the masses of Venus and the sun, and inversely as the square of the distance between their centres; and this is precisely equal to the force with which Venus attracts the sun. What are the implications of this law? If Venus and the sun were the only members of the solar system, Newton's law would lead strictly to the first and second laws of Kepler. But there are actually many other planets and bodies in the solar system, and each is attracting Venus according to the law of gravitation; for example, at a given instant the earth is attracting Venus with a force (directed towards the earth) proportional to the product of the masses of Venus and the earth, and inversely proportional to the square of the distance (at the moment) between them. But this force

exerted by the earth is excessively minute as compared with the force exerted by the sun, for the sun's mass is a third of a million times the mass of the earth. Accordingly, the orbit of Venus is not strictly an ellipse, but very nearly so; the minute divergencies due to the earth and other planets—generally too small to be detected by the observational appliances of Kepler's time—are called perturbations. On Newton's law of gravitation was reared the great mathematical structure of Dynamical Astronomy, which concerns itself with the exact calculation of a planet's orbit (or the orbit of a satellite) as disturbed by the attractive influences of every other planet or satellite.

We have said that Newton's law of gravitation led to the verification of Kepler's third law. But it did more. It gave the third law in a more complete form. As amended by Newton, it should be: "The mathematical expression given by the square of the period of revolution of a planet about the sun, multiplied by the sum of the masses of the sun and planet, and divided by the cube of the average distance of the planet from the sun is a universal constant, and is, therefore, the same for each planet." In Kepler's statement of the law, mass does not appear; the two forms of the law are almost completely reconcilable numerically, since the planetary masses are minute in comparison with the sun's mass (the most massive planet is Jupiter, with a mass a little less than one-thousandth part of the sun's mass), so that "the sum of the masses of the sun and planet" in the previous sentence is effectively the sun's mass which, being constant, does not appear in Kepler's form of the law. But from Newton's form of Kepler's third law a simple method of estimating the masses of planets which are accompanied by satellites is opened up. Taking first the planet Mercury, for example, we know its period of orbital revolution around the sun and its mean distance from the sun; neglecting its mass in comparison with the sun's mass, and taking the latter as the unit of mass, we can compute very easily the value of the constant referred to in the Newtonian form of Kepler's third law. Now consider Jupiter and one of its satellites; the law is applicable to the orbital motion of the satellite around its primary, and we have already deduced the numerical value of the constant. We know the distance of Jupiter in terms

of the astronomical unit of length, and from the observation of the satellite's orbit we deduce the value of its mean distance from Jupiter. We know also from observation the period of the satellite's revolution around Jupiter. Hence, the law gives us the sum of the masses of Jupiter and the satellite, or effectively the mass of Jupiter expressed in terms of the mass of the sun as unit. It is found from the calculation that the sun is 1047 times more massive than Jupiter. By a similar procedure, the sun's mass is found to be 330,000 times the mass of the earth. The mass of Mercury and Venus cannot be found in this way, as they do not possess a satellite; the effect of their perturbations on the earth's orbit provides the data from which their masses are estimated.

Two of Newton's deductions from the law of gravitation may be briefly noticed. The first related to the perplexing phenomenon of the precession of the equinoxes discovered eighteen centuries before by Hipparchus. Newton himself had shown as a result of his universal law that the figure of the earth must be spheroidal, thus confirming in a general way the pendulum experiments made a few years earlier. Now from the principles of Newtonian dynamics, the attraction of the sun or moon on a rotating sphere has no effect on the direction of the axis about which the sphere rotates. But with a spheroidal earth, flattened towards the poles, there is this difference. Owing to the fact that the orbital plane of the earth about the sun (or of the moon about the earth) is not coincident with the plane of the earth's equator, the attraction of the sun S (or of the moon) in Figure 23 on the bulging material (shown shaded) outside the sphere of diameter QP is not symmetrical about the line joining the centre of the earth to the sun (or the moon). The dynamical effect is a slow top-like motion of the earth of such a character that the direction of the axis of rotation QP revolves in a period of nearly 26,000 years around an axis perpendicular to the plane of the ecliptic.

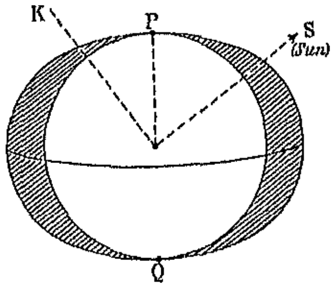


FIG. 23.

The phenomenon of the tides was likewise explained by

Newton. We may regard, for this purpose, the earth as a solid sphere covered with water. The attraction of the moon varies from one part of the ocean to another owing to the varying distances of these parts from the centre of the moon. The result is a heaping of the ocean around the place at which the moon is in the zenith and around the place on the earth diametrically opposite. On the meridian of these places it is high water. As the interval between successive passages of the moon across any meridian is about 24h. 50m. on the average, high water occurs at average intervals of 12h. 25m., the time of low water being intermediate. The sun exercises a similar but smaller effect. If the sun and the moon are near together in the sky, as at new moon, or diametrically opposite each other, as at full moon, they act, so to speak, together, and the heaping is a maximum. The tides are then called spring tides. When the moon and sun are at right angles to each other as viewed from the earth, as when the moon is half-full, the high water at a place due to the moon synchronises with the low water due to the sun; the result is a diminished high water, and the tides are then called neap tides. Such is, in bare outline, Newton's gravitational theory of the tides without any of the complications that have attracted the attention of later mathematicians.

The year 1846—a little more than a century and a half after the publication of the *Principia*—witnessed the most spectacular and astonishing triumph of Newton's law of gravitation. Until 1781 the sun's family of six great planets (Mercury to Saturn) had remained stationary in number. The telescope had its toll of successes in the discovery of satellites and of the fleeting comets, but it had hitherto failed to extend the system of planets. In that year Sir William Herschel—then a professional musician with his keenest interests centred, however, in the study of the heavens—with his own home-made instrument, detected an object which he described as "a curious nebulous star, or perhaps a comet." Subsequent observations proved the strange object to be a planet—later named Uranus—moving in a great orbit exterior to the orbit of Saturn. The discovery of Uranus has often been described as a lucky accident; it was rather a just reward for the persistence and patience with which Herschel devoted every available minute

to the systematic survey of the heavens, a tribute to his skill as an observer and a hall-mark of the excellence of his telescopes. Uranus had actually been observed on several previous occasions—as a star—and these older observations, combined with those made in years subsequent to its discovery, enabled the mathematical astronomers to calculate its orbit with great precision and to predict its position at any future time. But as the years went on it was noticed that Uranus did not move quite according to theory; the greatest discrepancy never exceeded 2′, apparently not a very large error, but, nevertheless, one for which there was not at the time an adequate explanation. In arriving at the theoretical positions of Uranus the effects due to the gravitational attraction of the planets on Uranus were, of course, fully taken into account. Was Newton's law of gravitation not quite accurate, or was there some other undiscovered agency which was responsible for the observed anomalies in the motion of Uranus? On July 3, 1841, a young undergraduate of St. John's College, Cambridge—John Couch Adams, by name—wrote the following memorandum, which is now preserved in St. John's College Library: "Formed a design, at the beginning of this week, of investigating as soon as possible after taking my degree the irregularities in the motion of Uranus which are yet unaccounted for, in order to find whether they may be attributed to the action of an undiscovered planet beyond it; and if possible, thence to determine the elements of its orbit, etc, approximately, which would probably lead to its discovery." After graduating as Senior Wrangler in 1843, Adams put his design into execution. The principal data of the problem consisted of the relatively minute differences, at various dates, between the observed positions of Uranus and the positions calculated in full according to the law of gravitation; and these small differences, in the skilful hands of Adams, were the means whereby, eventually, an unknown planet was to be located in the sky with almost unerring precision. In September 1845, Adams communicated the results of his calculations to Professor Challis, Director of the Cambridge Observatory, who passed them on to Sir George Airy, the Astronomer Royal. The latter, on July 9, 1846, suggested that Challis should undertake the search for the hypothetical planet in that part of the sky indicated by the

calculations of Adams. Owing to its predicted great distance, the planet would almost certainly be a faint object, indistinguishable in appearance from a feeble star; its planetary character, consequently, would probably only be detected by its gradual motion relative to its stellar neighbours in the sky. On July 29, 1846, Challis began the search. As he had no charts of that part of the sky giving the exact positions of the stars, his method was the laborious one of determining the positions of all the stars within the region specified by Adams, redetermining the positions on subsequent dates and comparing his observations, star by star, made on two or more dates. The unknown planet, if it were observed at all, would be revealed by unmistakable changes in its position relatively to the stars. This method of search, if slow, was sure. Unfortunately, Challis was in no hurry to compare his observations, and although he had actually observed the new planet on August 4 and August 12 as a "star," his failure to make promptly the all-important comparisons lost him the prize so nearly within his grasp.

On November 10, 1845, the distinguished French astronomer, Le Verrier, presented the first of three papers to the French Academy on the subject of the perturbations of Jupiter and Saturn on Uranus. In the second paper (June 1, 1846), he concluded that the anomalies in the motion of Uranus could only be explained by the action of an unknown planet, and the position he assigned to it was only 1° different from that calculated by Adams. In the third paper (August 31, 1846), he announced the details of the orbit of the unknown. In his address to the British Association on September 10, 1846, Sir John Herschel—after referring to the past year's discoveries (a minor planet had been found)—went on to say: "It has done more. It has given us the probable prospect of the discovery of another. We see it as Columbus saw America from the shores of Spain. Its movements have been felt, trembling along the far-reaching line of our analysis, with a certainty hardly inferior to that of ocular demonstration."

The circumstances were, indeed, remarkable and unprecedented in the history of science. From the minute irregularities of a planet's predicted motion, two mathematicians, one a youth, the other an experienced astronomer, armed only

ith the resources of brilliant mathematical ability, had dependently and unknown to each other, and by different ethods, announced almost simultaneously to the practical stronomer: "Point your telescope in such and such a direcon and there you will see a faint star-like object, which you ill soon recognise as a great planet moving around the sun an immense orbit, half as far away again as the most remote the known planets."

Le Verrier invited Dr. Galle, of Berlin Observatory, to carry it the search. The former's letter was received by Galle on eptember 23, 1846, who lost no time in setting to work, and iat same evening noticed what looked to be a star in a position ot marked on a recently-published chart of that part of the cy. The next night the suspected object had clearly moved i the interval. All doubt as to its character was dissipated ompletely. The object was no other than the hypothetical lanet of Adams and Le Verrier, now a visible reality. Like Iranus, the new planet—named Neptune—had been observed n previous occasions as a star, but it is fortunate that its iscovery was not made by simple telescopic observations—lthough this would have been a notable achievement—for cience would have been the poorer by the loss of one of the reatest triumphs in the realms of abstract thought.

The radius of Neptune's orbit is nearly 2,800,000,000 miles nd the period of revolution around the sun is about 165 ears. Since its discovery Neptune has traversed but little iore than a half of its majestic orbit. Is Neptune the most emote of the sun's family of planets, or is there beyond Neptune still more distant dependent of the sun? It is difficult to elieve that in the last half-century of almost incessant photoraphing of stellar regions that a planet, comparable in size vith the smallest of the eight great planets, could have escaped letection. If at some future time there should be unmistakable vidence (and at present there is little) that Neptune is deviating rom its predicted orbit, the methods of Adams and Le Verrier could be applied once again, and telescopic detection vould follow as surely as in the case of Neptune. But we are eaching out into the world of speculation and surmise; at present it is believed that Neptune marks the outermost limit of the planetary system.

## CHAPTER IV

### THE TELESCOPE

ASTRONOMICAL telescopes are divided into two classes—refracting telescopes and reflecting telescopes.

When a ray of light falls on a transparent substance, such as glass, its course through the glass is deviated according to well-known optical laws. In Figure 24, let AB represent the direction of a ray of light in air falling on a slab of glass with parallel plane faces. At B the ray is said to be refracted at the surface between the two media, air and glass, and its path BC in the glass is such that if PBQ is perpendicular to the surface of the glass, BC lies in the plane ABP, and the angle QBC is less than the angle ABP; there is a definite relation between these angles depending on the optical properties of air and glass. At C the ray emerges along CD, which is parallel to its initial direction AB. The laws of refraction are the basis on which the main property of a lens depends. The bounding surfaces of a lens are spherical, and the path of a ray of light incident on one surface can be traced out in its passage through the lens according to the laws of refraction. The light from a distant object, such as a star, may be regarded as a bundle of parallel rays, and it is found that the effect of the lens (such as is shown in Figure 25) is to cause the rays to converge to a point F. If the line CF is coincident with the line joining the centres of the spherical surfaces of the lens, the distance CF is called the focal length of the lens. If a photographic plate is placed at right angles to CF (the axis of the lens) at a distance from the lens equal to the focal length, then each individual ray of light from the star falling on the lens registers its effect

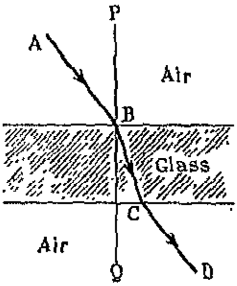


FIG. 24.

on the plate at the same point. The result is a photographic image of the star, which is the sum total of these individual effects. The character of the image thus depends on the area of the lens or object glass, as it is usually called, exposed to the incident star light—or, more strictly, on the square of the diameter AB of the lens. Thus for a given exposure the collecting power of a lens of 12 inches diameter is four times that of a lens of 6 inches diameter. The arrangement described is simply that of the ordinary camera, and, in principle, this is the form of the photographic refractor. The property of a lens which we emphasise here is its light-gathering power—the bigger the lens the greater is the amount of light falling on it and collected in the image.

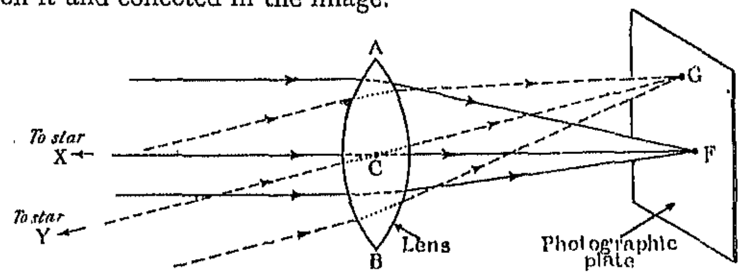



FIG. 25.—PRINCIPLES OF THE PHOTOGRAPHIC TELESCOPE.

In Figure 25 we suppose that the rays from the star X incident on the lens are parallel to the optical axis CF. Let CY be the direction of another star (in Figure 25 the broken lines represent the bundle of incident rays from this star, their paths through the lens and their convergence to a focus on the plate at G). Now the angle XCY is the angle by which the two stars are separated in the sky, and this angle is equal to the angle GCF. Consequently, the greater the focal length CF the greater will be the separation GF of the images on the photographic plate. An important department of astronomy is occupied with the photographic measurement of minute angles of the order of one hundredth (or less) of a second of arc ; success is only possible if the corresponding displacement on the photographic plate can be accurately measured ; thus an adequate telescopic focal length and a sufficiently accurate measuring machine are both necessary. The Yerkes Refractor, for example, has an object glass 40 inches in diameter, with a

focal length of 64 feet; an angle of 1″ in the sky is therefore represented on the photographic plate by a distance of one-tenth of a millimetre, or four-thousandths of an inch approximately, and distances one-hundredth part (or less) of this are capable of measurement.

The eye is optically a lens-system which receives a bundle of parallel rays from a distant object and brings them into focus on the sensitive retina. In Figure 26 the object glass of the telescope converts the incident parallel beam from a star into a converging cone of rays passing through the point F. If a lens PQ is placed beyond F at R, such that F is also the focus of this lens, the cone of rays diverging from F will be converted into a parallel beam, which on entering the eye will be brought to a focus on the retina, and the star will therefore

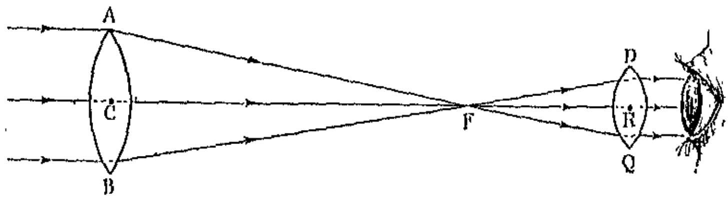



FIG. 26.—PRINCIPLES OF THE VISUAL TELESCOPE.

be seen sharply. The diameter of the pupil of the eye (the clear aperture of the eye-lens) is at most one-third of an inch. A telescope with an object glass of one inch diameter will therefore collect into the visible image nine times the amount of light entering the unaided eye alone; in other words, if there are two stars the first of which is just perceptible to the unaided eye and the other sends only one-ninth of the light of the first, the fainter will just be perceptible in a telescope with an object glass of one inch diameter. With the Yerkes telescope a star which sends only one fourteen-thousandth part of the light of the faintest naked-eye star will just be perceptible.

The magnifying power of a telescopic eye-piece is the ratio of the focal length of the objective to the focal length of the eye-piece; in any given telescope the magnifying power is increased by using eye-pieces of diminishing focal length.

Such are the principles of the simple astronomical refracting telescope—we cannot enter here into a more prolonged discussion of the modifications which have to be introduced into the

actual telescopes in daily use in the great observatories—and we pass on now to consider briefly the second class of astronomical telescope, namely the reflector. The reflecting telescope was invented by Newton in 1668. The law of reflection is as follows. A ray of light AB (Figure 27a) falling on a smooth, reflecting surface (or mirror) at B is reflected into the direction BC, which is such that if BN is perpendicular to the surface at the point B, the angle CBN is equal to ABN, the reflected ray being in the plane of AB and BN. The mirror used in the large astronomical telescopes has a paraboloidal surface which has the geometrical property of converting a beam of rays falling on the mirror MN and parallel, for example, to PQ in

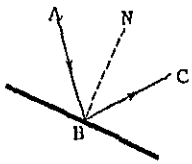



FIG. 27a.

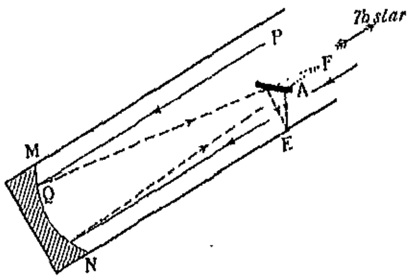



FIG. 27b.—PRINCIPLES OF THE REFLECTING TELESCOPE.

Figure 27b into a cone of reflected rays converging to a point F. The position of F is, however, obviously inconvenient. In the Newtonian form of telescope a small plane mirror placed at A at an angle of 45° to the axis of the mirror MN is fitted within the tube or girder-structure of the telescope and reflects the converging beam to a point E at the side of the tube, where either the image can be photographed or examined by means of an eye-piece. The focal length of the mirror is the distance between F and the mirror MN; the effective focal length, however, can be increased by various devices, into which we need hardly enter here. The largest reflector is the Hooker Telescope of the Mount Wilson Observatory in California; the mirror is of glass, the reflecting surface being silvered; its diameter is 100 inches; it is 13 inches thick and it weighs 5 tons. The focal length of the mirror is 500 inches, but, with the devices referred to, the effective focal length of the instrument can be increased to 135 and 250 feet. With this

last focal length the angle subtended by two stars 1″ apart in the sky is represented on the photographic plate by a distance of about one-sixtieth of an inch, or two-fifths of a millimetre. Plate II shows the 72-inch reflector of the Dominion Observatory, Victoria, British Columbia.

The fundamental instrument of astronomy is the meridian circle, which is shown diagrammatically in Figure 28a. It is essentially a refracting telescope mounted in a particular way. The telescope tube itself can rotate about an axis EW, which is horizontal and oriented east and west. The supports of this axis are carried on two massive piers. In the focal plane (F) of the object glass O there is placed a movable frame, carrying a number of parallel spider-lines. Figure 28b shows seven such

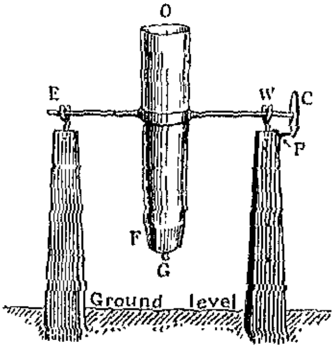



FIG. 28a.—PRINCIPLES OF THE MERIDIAN CIRCLE.

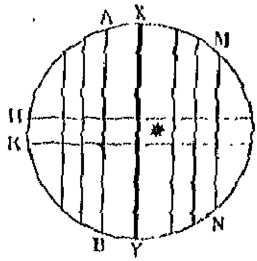
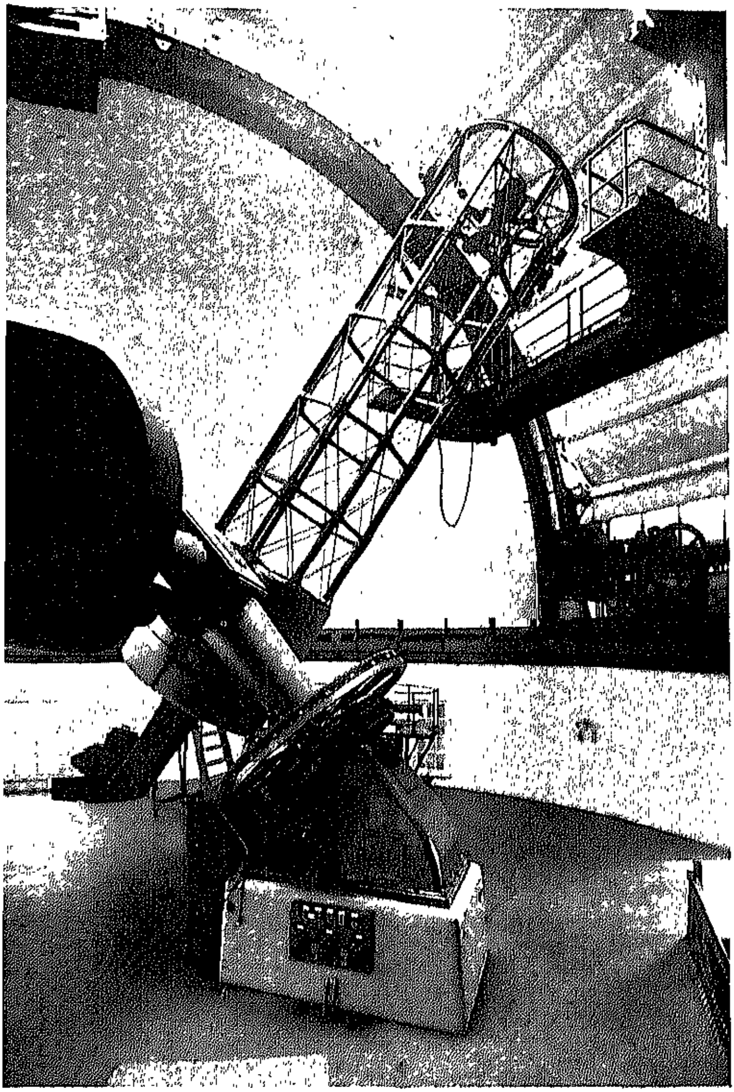



*FIG. 28b.*

wires, as they are usually called, in two groups of three on either side of a central wire XY. If the instrument is in perfect adjustment the line joining the centre of the object glass to the centre of XY moves in the meridian as the telescope is rotated about the axis EW. If the telescope is pointed, for example, towards the zenith, the observer will see such stars as come within the range of the telescope crossing slowly the field of view, and at the instant when a particular star appears to be situated on the central wire XY, the star will be on the meridian at that moment. If this instant be noted by means of a clock, keeping accurate sidereal time, then from the principles of Chapter II the sidereal time shown will be the right ascension of the star. In practice the times of the transits



:h Reflecting Telescope of the Dominion Observatory, Victoria, B.C

*Dominion Observatory, Victoria, B.C.*

of the star over several wires (for example, the seven wires of Figure 28b) are taken in order to ensure greater accuracy. Conversely, if the transit of a star whose right ascension is accurately known is noted on a sidereal clock, the error of this clock, if any, is obtained, and observations made from night to night determine the rate at which the clock is gaining or losing. Now the true sidereal time at any instant can be converted into the true Greenwich Mean Time (G.M.T.) at that instant; hence the errors of a clock rated for G.M.T. can be determined. To obtain as great precision as possible, several stars (known as "clock stars") are observed nightly, and the combined observations enable time at any instant to be determined with an accuracy of the order of one-hundredth of a second. The broadcasting of radio time signals from stations in direct communication with the standard clocks of an observatory is thus essentially dependent on the observation of stars made in the way indicated.

The framework of spider lines carries also generally a pair of horizontal wires—H and K in Figure 28b—which enable the zenith distance of the star to be measured. For simplicity we shall suppose that these wires are fixed in the frame and that the telescope can be delicately adjusted so that the star appears to travel across the field of view midway between the horizontal wires. The horizontal axis EW of the telescope carries a finely-graduated circle C, and a pointer P (or several pointers) with appropriate optical accessories enables a reading to be made on the circle corresponding to a particular position of the telescope in the meridian. If now the reading on the circle corresponding to the position of the telescope when it points accurately to the zenith can also be found, the difference between the two readings gives the zenith distance of the star observed. This latter reading is obtained as follows. The telescope is pointed downwards towards a bowl of mercury on or below ground level; with a suitable arrangement the wires can be illuminated so that the images of the wires, formed by reflection at the surface of the mercury, can be seen as well as the wires themselves. By moving the telescope gradually until the pair of images coincides with the pair of horizontal wires, the reading of the circle corresponding to the position of the telescope when it is pointed exactly vertically downwards

is obtained, and, consequently, by the addition of 180° the zenith reading is obtained. The latitude of the telescope is known, as the result of special observations, with all the necessary accuracy, and therefore the measured zenith distance of the star, combined with the known latitude, enables the declination of the star to be determined.

In this brief sketch of the meridian circle we have avoided many difficulties of practical importance; for example, the axis of rotation EW of the telescope is generally neither accurately oriented in the east and west direction, nor is it accurately horizontal. Such errors must be ascertained by subsidiary experimental and observational means, and their effects properly applied to every observation. We have omitted, too, for example, the effects of refraction—the slight bending of a ray of light from a star as it passes through the


FIG. 29.

earth's atmosphere. These and other matters call for great technical skill in the use of the instrument.

A great improvement in the accuracy with which the times of transit of a star over the wires in the field of view of the meridian or transit instrument has of late years been effected by means of the chronograph—which is simply an instrument recording the beats of a sidereal clock on a moving tape or rotating cylinder. In one form a tape is drawn by clockwork at a uniform rate under a pen attached to the armature of an electro-magnet. Every second the pendulum of a sidereal clock momentarily closes an electrical circuit; an electrical current flows through the electro-magnet, causing the pen to kick, the effect of which is recorded in the trace made on the tape (see the upper trace in Figure 29). A second pen which makes a trace parallel to the first can be actuated by the observer pressing a key at the moment the star crosses each of the vertical wires (this is illustrated in the bottom trace of Figure 29). Thus his observations are automatically and

permanently recorded. Another device is the travelling wire, which the observer moves across the field of view in such a way that the star is always on it; contact is made automatically at several points (corresponding to the several wires in Figure 28b), and the times recorded by the pen can be read at leisure.

The principal function of the meridian circle is the accurate determination of the right ascensions and declinations of all stars sufficiently bright to be observed with the instrument—the results of the observations made at the various observatories are incorporated in Star Catalogues, many hundreds of which must have been published since the time of Bradley (1693–1762), whose reign as Astronomer Royal was memorable for several remarkable discoveries and for the magnificent observations of stellar positions, which are of such value to-day. Although the charting of the fainter stars of the heavens is now taken over by the photographic telescope, the meridian circle remains the fundamental instrument for determining the right ascensions and declinations of the sun, moon, planets, and the principal stars. Such observations, combined with the law of universal gravitation, enable the positions of the bodies of the solar system to be calculated for many years ahead; the predicted positions and other phenomena are published in Almanacs, generally at the charge and under the direction of the various governments. The British publication is the *Nautical Almanac*, for which the Admiralty is responsible, and which—as its name implies—was originally prepared to give sailors the necessary astronomical information from which, as we shall see immediately, they are enabled to find their positions at sea.

The astronomical instrument in use at sea is the sextant, a simple hand instrument which enables the navigator to measure the altitude of a heavenly body above the sea-horizon. Figure 30 illustrates the principal features of the instrument. An arc KL of a circle, centre at Q, is supported by a metal framework. An arm QP with a pointer P is free to rotate about Q. Attached to this movable arm is a mirror I, set perpendicularly to the plane of the framework; attached to the latter is a glass H, also set perpendicularly to the plane of the framework. The bottom half of H is silvered, and therefore acts as a mirror, while the top half is clear. A small telescope

is fitted to the framework as shown in the figure. To find the altitude of a star above the sea-horizon, the observer holds the instrument with its plane vertical, so that he sees the line of the horizon in the field of view of the telescope, the rays of light from the horizon passing through the clear upper half of the glass H. He moves the arm QP carrying the mirror I until the image of the star is seen on the line of the horizon. When this is so the path of the rays from the star is as follows: the rays fall on the mirror I, are then reflected along the broken line IH; falling on the lower half of H (the mirror half), they

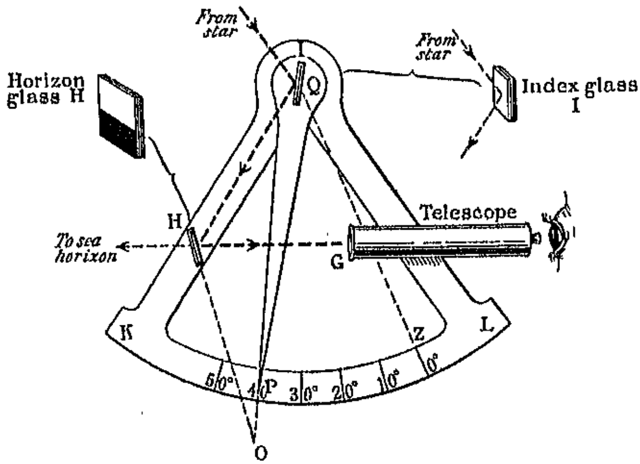



FIG. 30.—THE SEXTANT.

are again reflected, and then pass into the object glass G of the telescope; thus the star appears, in the field of view, to be on the line of the horizon. From simple geometrical considerations it is found that the altitude of the star is twice the angle between the planes of the mirrors I and H; this latter angle (HOQ in the figure) is measured by means of the pointer P and the graduated arc KL (the zero of the scale corresponds to that position of the movable arm such that the mirror I is parallel to the glass H). In this way the altitude of the star above the sea-horizon is obtained. After making the proper allowances for refraction and his height above sea-level (the sea-horizon appears depressed a little below the true horizontal plane by an amount depending on the observer's height above sea-level)

the observer obtains eventually the zenith distance of the star at the time of observation. This time is noted by means of a chronometer keeping, as near as possible, Greenwich Mean Time; the errors of the chronometer are easily found nowadays from radio time signals, and so the G.M.T. of the observation is accurately known. The important point to notice is that the complete observation gives the zenith distance of the star at a definitely known G.M.T. Now there is a point on the earth's surface at which the star is vertically overhead at this G.M.T., and the data in the *Nautical Almanac* allow this point to be calculated. Let it be U in Figure 31; it is known as the substellar point. Suppose for a moment that A is the true position of the ship; the zenith of the observer is then in the direction CA produced, that is in the direction CAZ. The direction in which the star is observed is AS, which is parallel to CUS, for the star is at a very great distance, and the zenith distance ZAS, which is the immediate result of the sextant observation, is consequently equal to the angle ACU. Now at the known G.M.T. of the observation the point U on the earth's surface is a perfectly definite and calculable point; the zenith distance of the star is also definitely known. Hence, the ship must be somewhere on a small circle BAD, all points of which are at the same angular distance from U, this angular distance being the zenith distance of the star derived from the sextant observation. The result of an observation of this kind is to locate the ship on a definite small circle on the earth's surface, called the position-circle.

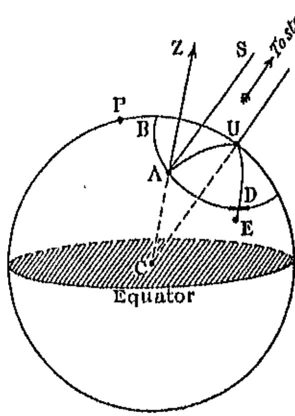


FIG. 31.

Now the navigator knows with fair accuracy the speed and course of his ship, and if he had to rely on these two factors alone he could tell what the approximate position of his ship would be at any time by simple plotting on a chart; a position obtained in this way is called a Dead-Reckoning position (D.R.). At the best this may be fairly near the true position of the ship at the particular time, but at the worst it may be so

badly in error—owing to unsuspected currents and the incalculable effects of wind and so on—that uncritical confidence in such an estimated position may result in danger to the ship. Now we have seen that a single observation of a star (or any heavenly body) shows the navigator that his ship is on a definite position circle at the time of observation ; also, at this particular instant he has a Dead-Reckoning position, which is somewhere near the true position of the ship. Let the approximate position be at E in Figure 31, and let the great circle joining U and E cut the position circle at D. The latitude and longitude of both U and E being known, the length of the arc UE can be calculated ; the arc UD is known from the zenith distance of the star ; hence ED—the distance of the Dead-Reckoning position E from the position circle—is obtained. As E is an approximation to the true position of the ship, and as the ship is known from the sextant observation to be somewhere on the position circle, the only part of the latter which really concerns the navigator is that small section of the position circle in the immediate neighbourhood of E. The bearing of the place U from E can be calculated, or, what is practically the same thing, the bearing of the star from the ship may be observed with sufficient accuracy by means of the compass. The all-important part of the position circle is thus at right angles to the bearing of the star. The navigator then proceeds to plot his results on the chart as follows (Figure 32). From E —the D.R. position on the chart—he draws a straight line ES in the direction given by the bearing of the star ; he marks off a distance ED which he has found as explained above ; he then draws a line XY at right angles to ES through D, and the conclusion is that his star observation places the ship at the particular instant of observation on the straight line XY, called the position line, as represented on his chart.

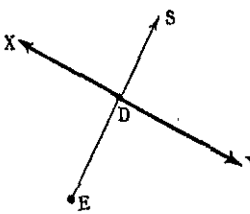



FIG. 32.
THE POSITION LINE.

To determine his position definitely, the navigator requires two such star observations. Suppose these are made simultaneously ; then each observation gives rise to a definite position line, and the intersection of the two position lines is

clearly the true position of the ship at the time of observation. If the observations are not made simultaneously the run of the ship is allowed for as follows. Suppose at 6 p.m. the result of a star observation is the position line XY (Figure 33), and that at 7 p.m. a similar observation of a different star is obtained. If the ship had been at F at 6 p.m., then at 7 p.m. its position would be at G, where the length and direction of FG are given from the ship's speed and course; similarly, if the ship had been at H at 6 p.m., then its position at 7 p.m. would be at K. It is clear that as the 6 p.m. observation places the ship somewhere on XY, then at 7 p.m. its position must be somewhere on UV, which is simply the line XY displaced parallel to itself in accordance with the ship's run between 6 p.m. and 7 p.m. Now at 7 p.m. the observation of the second star leads to the conclusion that the ship must lie on a position line such as LM. Hence, at 7 p.m. the ship's position is at A, the intersection of LM with UV.

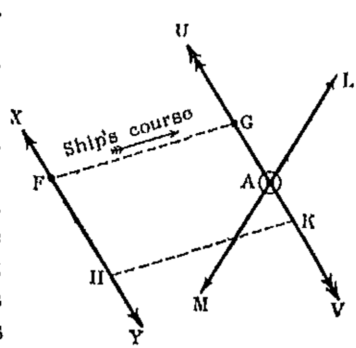


FIG. 33.

According to this principle it is not necessary to make observations of two different heavenly bodies, provided that a sufficient time is allowed to elapse between the observations so that the bearings of the body—and consequently the orientations of the two resulting position lines—differ by 30° or 40° at least. Two observations of the sun, for example, if separated in time by three or four hours, result in the position of the ship being determined at the time of the second observation. It is clear that, in this case, inaccurate estimates of the speed and course of the ship between the two observations are reflected in an erroneous displacement of the first position line, and therefore the position which the two sextant observations finally give is subject somewhat to error.

## CHAPTER V

### THE SUN

THE importance of the sun in relation to organic life on the earth is a commonplace that hardly requires emphasis. The sun is the source of an apparently never-ending stream of light and heat energy, without which life—as we know it—would be an impossibility. The moon and the planets are non-luminous bodies made visible to us on the earth by reflected solar light; of the great bodies of the solar system the sun itself is the only one that is self-luminous. The telescope reveals millions of points of light, the visible evidence of almost countless stars, self-luminous like the sun; the presumption is that our sun is but a unit in the great galaxy of stars. The study of the sun, then, is the study of a star—our nearest star—but the question whether the sun is to be regarded as a typical example of the stellar host in general must be relegated for later consideration. But the study of the sun has more than narrow astronomical interest to commend it—we shall see in the next chapter that the problems associated with the constitution of matter can be profitably studied in the great solar laboratory. In the present chapter we shall confine ourselves to the more direct problems and phenomena concerning the sun.

The sun, first of all, is a spherical body, and we can easily measure the angle which a diameter subtends at the earth; in round figures it is on the average $32'$ of arc. This angle is not quite constant from day to day, for as the earth revolves about the sun in its elliptic orbit the distance between the sun and the earth varies slightly during the year; accordingly, when the earth is nearest the sun, the angle subtended at the earth by a solar diameter is greatest, and *vice versâ*. This variation is comprised between the limits $32'{\cdot}6$ and $31'{\cdot}5$. Let us restrict our attention to the angular semi-diameter of the sun corresponding to the average distance of the earth from the sun,

If we know the latter in terms of miles, the observed value of the former enables us to calculate the diameter of the sun in miles. We shall anticipate the subsequent description of the methods employed in measuring the distance of the sun from the earth by stating meanwhile the result of such investigations —the average distance of the earth from the sun is found to be 92·9 million miles. We have now the simple geometrical problem: what is the length of the solar diameter in miles which subtends an angle of $32'$ at a distance of 92·9 million miles? The answer is that the sun's diameter is 865,000 miles, a little over a hundred times the diameter of the earth. When we compare the volumes of the sun and the earth we find that the volume of the sun is 1,300,000 times the volume of the earth.

The next step is to investigate the amount of matter in the sun, that is, the sun's mass. We have already in Chapter III shown the method by which the ratio of the sun's mass to the mass of a planet such as Jupiter or the earth is determined. In particular we stated the result with reference to the earth, namely, that the sun is 330,000 times more massive than the earth. If we require the mass of the sun expressed, for example, in tons, we must first of all know the mass of the earth in tons. The earth's mass has been measured by several methods, all based on the law of gravitation. We state the answer: the mass of the earth is about 5000 million million million tons. The sun's mass can then be calculated in tons. It may seem at first sight that this particular information can have very little practical or theoretical importance; we shall see, however, when we consider the internal constitution of the stars, that this numerical estimate of the sun's mass has far-reaching consequences in the current theory of stellar evolution.

From the volume and mass of the sun the average density of the solar matter is found to be 1·4; this means that the mass of the sun is 1·4 times the mass of an equal sphere of water. The average density of the earth is 5·5, which is thus about four times the sun's density.

We have had occasion to state the result of investigations into the average distance of the earth from the sun (the astronomical unit of distance), and some account of the methods by which it has been measured will now be given. It is a problem

in surveying, alike in principle to the familiar methods of terrestrial surveying. In a land survey, if the distance of a distant object C from a point A is required, a suitable base-line AB is measured accurately (Figure 34) and the angles between the directions of AC and AB and between the directions of BC and BA are obtained, for example, by means of a theodolite. The elements of the triangle ABC can then be calculated; in particular, the distance of C from A.

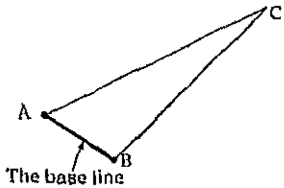



Fig. 34.

In land surveys it is always possible to choose a base-line of sufficient length, in comparison with the distance to be determined, to lead to a result of high accuracy. In astronomical surveys, on the other hand, our measured base-line cannot exceed the diameter of the earth, so that it is always less than 8000 miles. To illustrate the simplest example of astronomical survey we shall show how the distance of our nearest celestial neighbour, the moon, can be measured. For simplicity we shall assume that there are two observatories, A and B, one in the northern hemisphere and the other in the southern, on the same meridian of longitude PABQ (Figure 35). The moon will therefore transit at the same moment at each observatory, and by means of the transit circle the zenith distance of the moon (in practice a prominent lunar mountain is observed) can be measured at each of the stations A and B. At A the direction of the zenith is CAY, and the moon's zenith distance measured is the angle

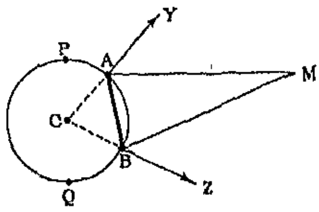



Fig. 35.—Measurement of the Moon's Distance.

YAM; at B, the direction of the zenith is CBZ, and the zenith distance measured is the angle ZBM. The latitudes of A and B are presumed known, so that the elements of the triangle CAB can be found—in particular the distance AB (the base line) and the angles CAB and CBA. Then since the angles YAM and MBZ are known from the observations, we obtain the angles MAB and MBA, which, with the length of the base line AB, reduce the problem to the simple one illustrated in

Figure 34. Thus the distance AM is found, and an additional step in calculation leads to the distance MC. In this way the distance between the centres of the earth and moon is measured —the average distance is 240,000 miles. This is, in bare outline, the principle adopted; essentially it is a fairly straightforward application of the simple method of the land-surveyor.

But we cannot proceed in the same way to measure the distance of the sun. In the first place, the sun is not a solid body like the moon, with definite and stable landmarks such as the lunar peaks, which can be accurately observed. In the second place, the distance of the sun is so great as compared with the maximum base line on the earth that the angle subtended at the sun by this base line is much too small for accurate measurement by the transit circle. At first sight the problem of measuring the sun's distance appears intractable. But we have seen that Kepler's third law is sufficient in itself to map out the planetary orbits on any arbitrary scale that we choose to employ, for since the periods of revolution of the planets are accurately known, the ratio of the mean distances from the sun of any two planets can be calculated. For the earth, the distance of the sun is the astronomical unit of length, and consequently the mean distances of the other planets from the sun are found in terms of this unit. Thus we obtain a map of the solar system, and all we require in order to deduce the distance of the earth from the sun—expressed in miles—is the scale of the map. A map of England without a scale will not enable us to calculate the distance of York from London; but if it is known that the distance between Oxford and Cambridge is so many miles, this information will enable us to fix the scale of the map and then to deduce the distance of York from London in miles. So it is in the astronomical problem; if the distance of the earth from any planet can be measured at a particular time, the scale of the map of the solar system can be obtained, and in particular the distance of the earth from the sun can be expressed in miles.

The advantages of this procedure are apparent; a planet presents a comparatively small disc—a minor planet, in fact, cannot be distinguished, so far as appearance in the telescope is concerned, from a star—and observations can be made with comparatively small errors; a further advantage is that

the distance to be measured, when a suitable planet is observed for the purpose under consideration, is very much less than the distance of the earth from the sun. This latter point is illustrated in Figure 36, in which the orbits of the earth, Mars and the minor planet Eros are drawn. Let us first consider the orbits of the earth and of Mars; the former is almost circular, but the latter has a pronounced ellipticity. When the sun, the earth and a planet are in a straight line, the planet is said to be in opposition, so that at midnight the planet will be on

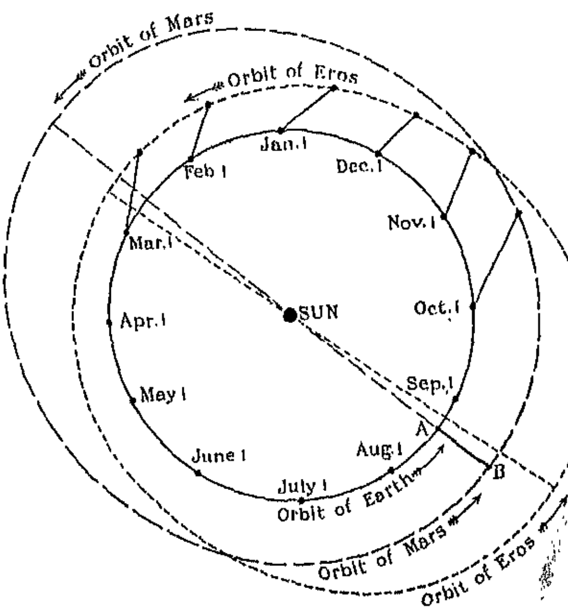



FIG. 36.

the observer's meridian. The most favourable opposition of Mars is that which occurs about August 24, when the distance between the earth (then at A) and the nearest point B on the orbit of Mars is about 35 million miles. The least favourable opposition is that which occurs in February—then the distance between the earth and the nearest point on the orbit of Mars is 61 million miles. The problem of the measurement of the sun's distance is reduced to the much simpler one of measuring the distance of Mars, which, given the most favourable circumstances, may be as near as 35 million miles. It was by a long

series of observations of Mars made on the Island of Ascension at the opposition of 1877 that Sir David Gill measured the distance of Mars and so arrived at a reliable value of the distance of the earth from the sun. But in 1898 a minor planet, called Eros, was discovered, which offered greater possibilities for the accurate determination of the astronomical unit of distance. The orbit of Eros is shown in Figure 36. It is seen that the orbit approaches much more closely the earth's orbit than does the orbit of Mars; at the most favourable opposition the distance between the earth and Eros is about 14 million miles. Extensive observations of Eros were made at the opposition of 1900–1 (to which reference will be made more fully later). The relative positions of the earth and Eros are shown in Figure 36 between October 1, 1900, and March 1, 1901.

What is the nature of the observations, and what is the base line adopted in practice? We shall suppose that in Figure 37 there are two observers, one at A and the other at B, A and B being two points on the surface of the earth, and that each is able to measure the angle between the planet M and a particular star S, as seen in the field of view of the telescope. If the observations are made simultaneously, the interpretation is as follows. (For simplicity we shall suppose that the direction of the star is in the plane ABM.) For the observer at A the angle between the direction of the planet and the direction of the star is MAS. The observer at B measures the angle between the direction of M and the direction of the star, that is, the angle MBT; but as the star is at a distance almost infinitely great as compared with the distance AB, BT is parallel to AS, and the difference in the angles measured at A and B is simply the angle AMB. This completes the data required for the solution of the problem, and the distance of the planet from the earth is then a matter of calculation. But it is unnecessary to have a base line defined in this way, that is, with an independent observer at each end of it. The rotation of the earth

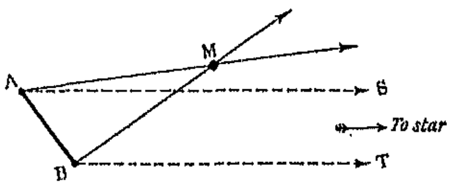



FIG. 37.

carries an observer through a distance equal to the earth's diameter in the course of twelve hours, provided he is at the equator; for an observer in 60° north or south latitude the distance is just half of this. Consequently, if a single observer stationed at the equator makes the kind of observation described above at 6 p.m. and again at 6 a.m. on the following morning, his point of observation has been moved 8000 miles in the interval, and this provides him with the necessary base line. Corrections for the amounts by which the earth and the planet have advanced along their respective orbits in this interval must necessarily be taken into account.

Actually the position of the planet is measured in the telescope or on a photograph with reference, not to a single star, but to several; the process is fundamentally a simple survey of several fixed marks (the stars) and a wandering object (the planet). A photographic plate with an exposure, say, of one minute will record the position of the planet with reference to half a dozen or more stars in its immediate neighbourhood; several hours later—let us suppose—a similar photograph will record the new position of the planet with reference to the same stars, and the displacement of the planet in this interval can accordingly be measured (this displacement corresponds to the angle AMB in Figure 37). The procedure may be conveniently represented diagrammatically (Figure 38). The small dots at A . . . E represent the images of the stars impressed on the plate by an exposure, say, at 6 p.m.; the small dot, marked P, represents the image of the planet for that exposure. Suppose that the plate is not removed from the telescope, so that it is ready for another exposure, say, at 6 a.m. (the plate, however, is supposed to have been altered slightly in its position on the telescope, so that the 6 a.m. set of images of the stars do not fall exactly on top of the first set of images). The 6 a.m.

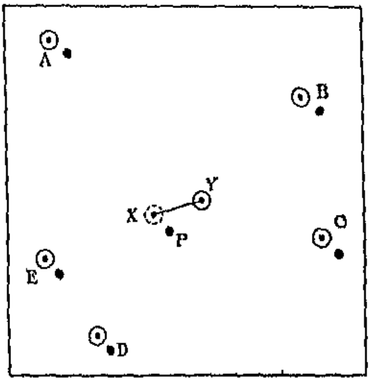



FIG. 38.

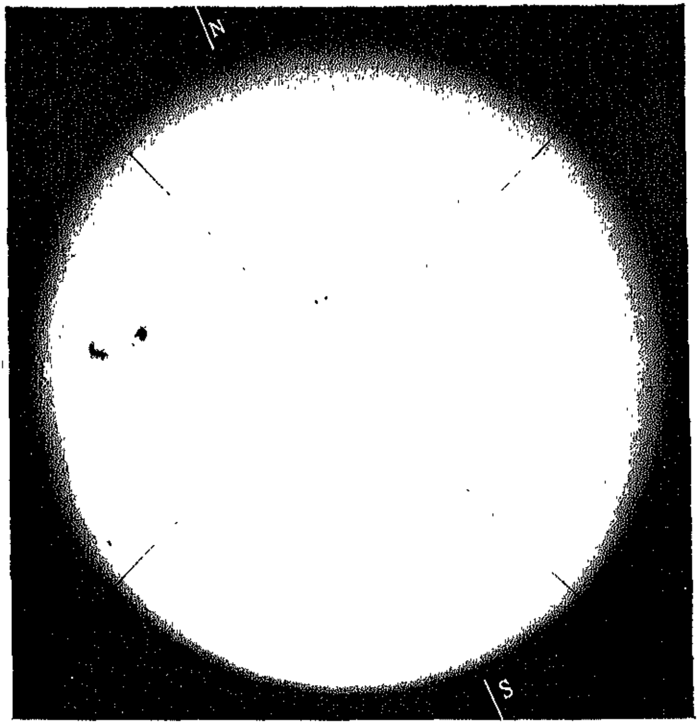
images are marked with a circle so as to distinguish them from the first set at 6 p.m. On the plate, then, the 6 a.m. image of each star appears to be displaced relatively to the 6 p.m. image by a constant and measurable amount. If the planet were at an infinite distance its image at 6 p.m. and 6 a.m. would be displaced by the same amount as for the stars; that is to say, from P to X. But owing to its comparative nearness to the earth the direction of the planet with reference to the stars will have altered owing to the observer's change in position, and its image will be, let us say, at Y. The displacement from X to Y is therefore the displacement corresponding to the change in the directions of the planet as viewed from the two ends of the base line defined by the observer's position in space at 6 p.m. and at 6 a.m. The problem, then, in its simplest aspect is to measure in inches, or fractions of an inch, the arbitrary displacements of the stars A, B, etc. From these measures an accurate estimate of the displacement P to X is obtained. The images of the planet on the plate are of course at P and Y; the displacement P to Y is measured, and finally the displacement X to Y is deduced. The scale of the photographic plate is known, for we simply correlate the distance measured, for example, in inches or fractions of an inch between the images of two stars with their angular separation on the celestial sphere. Thus the angle subtended by the base line at the planet (analogous to the angle AMB in Figure 37) is obtained.

At the 1900–1 opposition of Eros, no less than eighteen photographic telescopes were actively engaged in what was known as the Eros campaign. At the nearest approach of Eros to the earth, the angle subtended by the earth's diameter at the planet was about 53 seconds of arc. On the Cambridge plates this angle corresponds to a displacement of the images (XY in Figure 38) of a little more than one-twentieth of an inch. The practical problem before co-operating observatories was to attempt to measure the displacements of the planet's images with such an accuracy that the final calculated distance of the sun would be correct to at least one part in a thousand. It is unnecessary here to go into details as to the great difficulties and immense labour which the Eros campaign involved both for the co-operating observatories and especially for

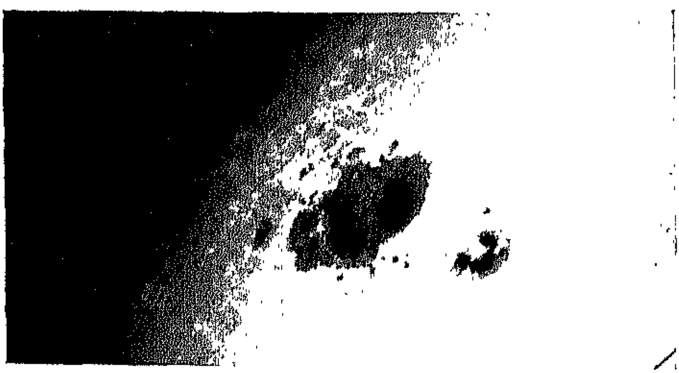
Mr. A. R. Hinks, of the Cambridge Observatory, who was responsible for the co-ordination and discussion of all the Eros observations. The final result—obtained after many years' work—is that the angle subtended at the sun by the earth's radius is 8″·807; this fundamental angle is called the *solar parallax*. From it and the known radius of the earth the distance of the sun from the earth is found to be 92·9 million miles.

The next favourable opposition of Eros occurs in 1930–31, and already preparations are on foot for repeating the kind of observations which have just been described in outline. The mere fact that a large body of astronomers propose to devote several months to a somewhat exacting observational programme, and several years more to the laborious calculations which the problem entails, is a sufficient indication of the importance attached to an accurate knowledge of the solar parallax.

It is not our purpose to give an account of all the other direct and indirect methods by which astronomers have attempted—for nearly two centuries—to arrive at the fundamental unit of distance in astronomy; it is almost sufficient to mention that every celestial phenomenon which can be utilised in this connection has been induced to pay its contribution to the calculation of the solar parallax. But brief reference may be made to an indirect method which depends on the phenomenon of aberration. The usual non-technical explanation (by analogy) of this phenomenon is as follows. In a rainstorm, if one is armed with the more or less adequate protection of an umbrella, one tilts the umbrella slightly forward—if the raindrops are falling vertically—by an amount which is determined empirically, but which ultimately depends on the speed of the raindrops and the speed of the walker. If the raindrops are falling at an angle to the vertical, a similar adjustment of the tilt of the umbrella is made; in any case, if one has become wise by experience the direction in which the umbrella is held to afford the maximum protection is somewhat different from the direction in which the raindrops are falling. The stream of light from a star is travelling with the stupendous speed of 186,000 miles per second; the earth and the observer are travelling round the sun with a speed which if great




(*a*) Direct Photograph of the Sun.
*Royal Observatory, Greenwich.*



(*b*) The Great Sun-Spot, January 20th, 1926.
*Royal Observatory, Greenwich.*

compared with ordinary standards is a small but yet appreciable fraction of the velocity of light. The consequence is that for any one observation of a particular star, the telescope requires to be pointed in a direction slightly different from that in which it would be pointed if the earth were really stationary with reference to the star. This direction changes from day to day; the changes are easily detected if the right ascension and declination of the star are measured with the transit circle at intervals throughout the year. The effect of aberration—as this phenomenon is called—is that the star appears to describe on the celestial sphere a small ellipse, of which the semi-major axis is found by measurement to be 20″·5. From this value and the known velocity of light the speed of the earth in its orbit is deduced. The orbital period of revolution of the earth is known, and therefore the size of the orbit is easily found, from which the distance of the earth from the sun is finally obtained.

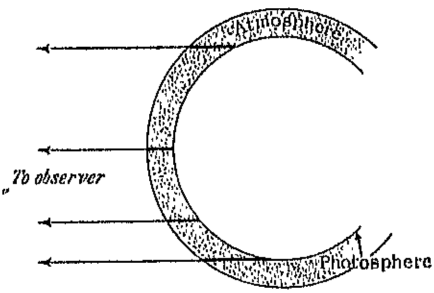



FIG. 39.

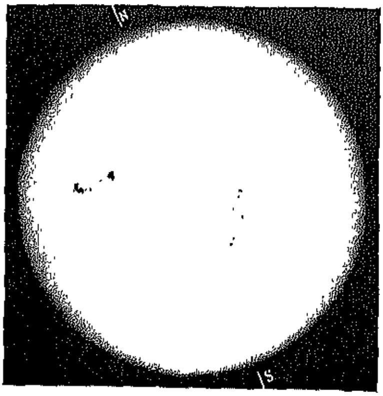
We proceed now to describe some of the simpler characteristics of the physical appearance of the sun, which are illustrated in the photograph shown in Plate III (*a*). The sun is a vast ball of gas, which radiates into space vast quantities of light and heat energy, only a very minute fraction of which is trapped by the earth. The surface from which this stream of radiation pours is called the *photosphere*. A feature of the photograph—very much more pronounced than in the visual appearance of the sun—is the shading of the brightness of the solar disc towards the edge (darkening towards the limb, as it is called). This suggests the presence of an absorbing atmosphere, for its effect would be greatest at the limb, where the photospheric light passes through a much greater thickness than at the centre of the disc, as the accompanying Figure 39 illustrates. Astronomers divide the solar atmosphere into two parts: firstly, the *reversing layer*, extending a few hundred miles above the photosphere and gradually merging into it; and, secondly,

E

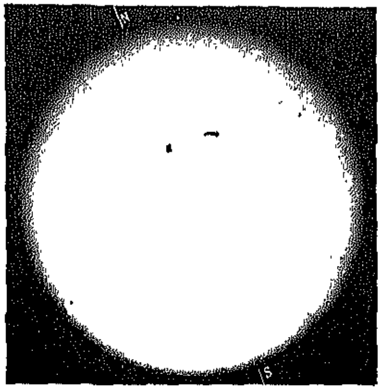
the *chromosphere*, merging at its lowest levels into the reversing layer and extending to a height of at least 5000 miles above the photosphere. The significance of this distinction will be apparent in the succeeding chapter; meanwhile, it is sufficient to mention that the stratum of the reversing layer contains the vapours of many familiar terrestrial elements under conditions that can be approximately realised in the laboratory, and that the chromosphere is a sparser envelope containing principally incandescent hydrogen and the incandescent vapour of calcium.

But the principal feature of the photograph is the dark, irregular markings, called sun-spots, dark only by contrast with the much greater brightness of the photosphere. In Plate III (*b*) there is a photograph of the great spot visible in January, 1926. In the neighbourhood of sun-spots and elsewhere on the disc, but best seen near the limb (*i.e.* the edge), are bright patches, called *faculæ* (Plate III (*a*)), luminous clouds floating high up in the solar atmosphere. In addition, the solar surface appears mottled; its appearance has been likened to that of rough drawing-paper. Finally, the sun is surrounded by a vast envelope, of extreme tenuity, only seen when the sun is totally eclipsed; this is the *corona*.

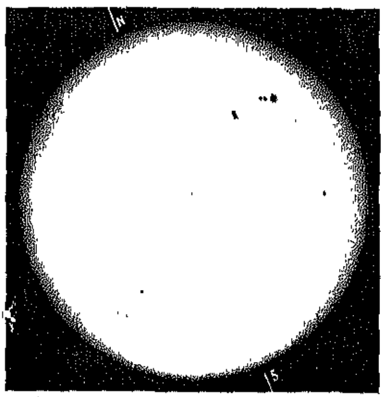
There are many records of sun-spots having been seen with the naked eye long before the invention of the telescope, but it was only after 1610 that they could be studied at all adequately. It was then noticed that these dark markings appeared to move slowly from east to west over the solar disc, the interval between a spot's appearance on the east limb and its disappearance on the west limb being about 13 or 14 days, approximately. (See Plate IV, which illustrates the movement of the spots across the sun.) At first, the nature of sun-spots was not definitely understood—in fact, the black markings were attributed to the transit of Mercury or of hypothetical small planets across the solar disc—but Galileo soon showed that the spots were phenomena belonging to the sun itself. It followed, then, that if the spots were actual markings on the solar surface, the sun was a body rotating about an axis in a period of about 26 days. Compared with the gaseous sun, the earth is a rigid body, and there is no ambiguity in referring to the period of rotation of the earth about its axis. But the



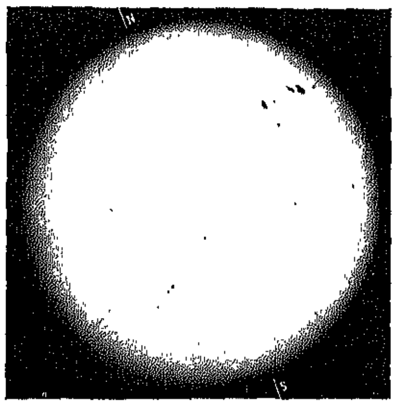

(*a*) Sept. 17, 1926.




(*b*) Sept. 20, 1926.




(*c*) Sept. 22, 1926.




(*d*) Sept. 23, 1926.

Direct Photographs of the Sun to show rotation.

*Royal Observatory, Greenwich.*

sun is the very antithesis of rigid, and the period of the solar rotation as determined from the movement of sun-spots is a less definite conception. The movement of the spots determines the solar axis and solar equator; accordingly the latitude (on the sun) of a particular spot can be specified.

For over 200 years no progress was made in the elucidation of the phenomena presented by the sun-spots; there was an apparent capriciousness about their appearance and disappearance, their size and numbers; some endured but for a few days, others continued to be seen for several months; some were large and some were small; their numbers varied apparently haphazardly from month to month and year to year. In 1843, Schwabe of Dessau, an apothecary interested in astronomy, announced as the result of eighteen years'

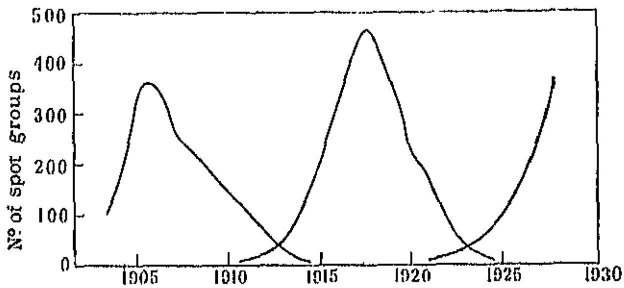



FIG. 40.—SUN-SPOT FREQUENCY CURVES.

patient and unrelaxing observations of the sun, that the number of sun-spot groups varied from month to month and year to year in a definitely regular way in a period of ten years —modified by subsequent investigations to 11·1 years on the average. The features of the sun-spot cycle are as follows: at a sun-spot minimum the disc of the sun may be for weeks and months entirely or almost entirely free from spots; spots gradually appear in ever-increasing numbers until after about four and a half years a maximum is reached; the numbers then decrease until after about six and a half years more the sun-spot minimum is reached and the cycle begins afresh. Figure 40 shows the curves obtained from the observed yearly number of sun-spot groups for the last two cycles. At the time very little notice was paid to Schwabe's discovery, but in 1851 Lamont, of Munich Observatory, announced a periodicity in magnetic

phenomena of a character almost identical with that of sun-spots. A magnetic needle, when freely suspended, points to what is known as magnetic north, distinct from true north, which is defined with reference to the earth's axis of rotation. The needle generally undergoes minute daily fluctuations, and Lamont's discovery was that the extent of these fluctuations increased and decreased fairly regularly in a period practically identical with the sun-spot period. In 1852 an additional circumstance was pointed out independently by three scientists, namely, that the maximum disturbances of the magnetic needle corresponded exactly with the maximum spottedness of the sun, with a similar correspondence of the respective minima. The very extensive disturbances of the magnetic needle are described as magnetic storms, and it is now certain that these are generally associated with increased sun-spot activity. The presence of a large spot, however, does not always portend a magnetic storm—and *vice versâ*—but the general correlation between the two phenomena is now undeniable. The magnetic discoveries of Lamont and others drew increased attention to the earlier discovery of Schwabe, and the latter received well-merited recognition in 1857, when the Gold Medal of the Royal Astronomical Society was awarded to him. The president said, in the course of his address, on this occasion: "Twelve years he (Schwabe) spent to satisfy himself—six more years to satisfy, and still thirteen more to convince, mankind. For thirty years never has the sun exhibited his disc above the horizon of Dessau without being confronted by Schwabe's imperturbable telescope, and that appears to have happened on an average of about 300 days per year. This is, I believe, an instance of devoted persistence unsurpassed in the annals of astronomy. The energy of one man has revealed a phenomenon that had eluded even the suspicion of astronomers for two hundred years." That sun-spots come and go in a fairly regular manner is perhaps a most interesting fact about our luminary, but it is something more; it is the visible evidence of some far-reaching changes, regular and periodic in character within the sun, depending on physical and mechanical conditions not yet completely elucidated.

The knowledge of sun-spots so laboriously acquired was the incentive to a yet more intensive study by Carrington. The

results of his observations were as follows. At the beginning (minimum) of a new sun-spot cycle the spots appeared in solar latitudes around 35° north and south; as the cycle proceeded, the latitudes frequented by the sun-spots became lower and lower, so that when the maximum was reached—that is, when the spots were most numerous—the latitudes had become as low as 5° north and south. Moreover, spots were rarely seen within 5° of the solar equator, nor in latitudes higher than 35° north or south. The beginning of the new cycle saw the appearance of spots in or near latitude 35°, but for a year or more thereafter spots were still visible in latitudes round about 5°, as if the old cycle was loth to yield to the new. Carrington further showed that the period of rotation of the sun as derived from the observed movements of sun-spots depended on the latitude of the spot chosen for observation. Equatorial spots seemed to show that the sun rotated about an axis in about 25 days, whereas the spots met with in the high latitudes appeared to indicate a period of rotation of about 27½ days. The regular progression of length of period with solar latitude has been confirmed by other methods. We must bear in mind, however, the gaseous constitution of the sun and the fact that sun-spots are the manifestations of some phenomenon in the photospheric strata, and that each, like a terrestrial cyclone, for instance, has its own peculiar movements relative to the solar surface. We shall return to the subject of sun-spots in the succeeding chapter.

Of all the spectacles of nature, a total eclipse of the sun must surely take first place. We are assured by those who have been privileged to see the wonders of this phenomenon that neither pen nor brush is adequate to express its majesty. To the layman there is even something uncanny in the precision with which astronomers are able to calculate, years before, the circumstances of an eclipse—the particular belt on the earth's surface from which it is total, the beginning and end of totality at different points within this belt, and so on. An eclipse of the sun is caused by the interposition of the dark body of the moon between the earth and the sun. If the plane of the moon's orbit around the earth coincided with the ecliptic, that is, with the plane of the earth's orbit around the sun, an eclipse of the sun would take place at every new moon—at intervals

of about 29½ days. The circumstances are illustrated in Figure 41—obviously not drawn to scale.

At new moon the relative positions of the sun, the moon and the earth are shown; the unilluminated hemisphere of the moon is towards the earth. In this position the moon acts as a dark screen, blotting out all view of the sun from places between A and B on the earth—the figure shows the shadow cast by the moon—and at these places a total eclipse of the sun occurs. At places, such as C and D, the moon is only a partial barrier to the light from the sun; for example, at C the lower part only of the sun's disc is blotted out by the moon. At such places there is a partial eclipse of the sun. In a similar way, an eclipse of the moon occurs when the moon passes into the shadow cast by the earth. The factor that determines the

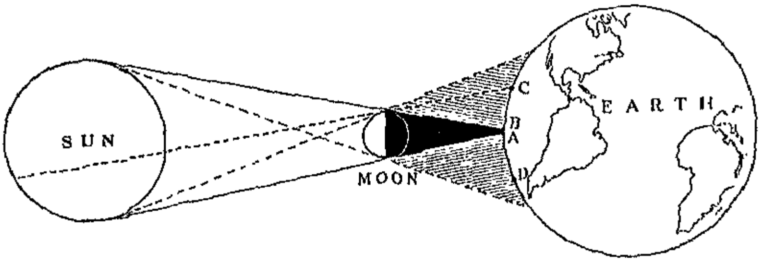



FIG. 41.—ECLIPSE OF THE SUN.

possibility of total eclipses of the sun is the magnitude of the angular diameter of the moon as compared with that of the sun. Now the angular diameter of the sun is about 32 minutes of arc; the average angular diameter of the moon is somewhat greater, so that actually the moon covers a rather larger part of the sky than the sun covers, and therefore the moon can block out the sunlight completely. It is, then, to be regarded as a circumstance, fortunate for the advancement of astronomical science, that the spatial relationships of the sun, moon and earth are as they happen to be; in fact, a very small decrease in the angular diameter of the moon relatively to that of the sun would render impossible this most sublime spectacle of a total eclipse of the sun.

We have assumed in the foregoing that the moon's orbital plane coincided with the plane of the earth's orbit around the sun; but this is not so, for the former is inclined to the latter

at an angle of about 5°. The circumstances are illustrated in Figure 42, which represents the celestial sphere centred at the earth E. Relatively to the earth the sun appears to describe amongst the stars a complete circuit of the heavens in 365¼ days—the ecliptic in Figure 42—and in 27⅓ days the moon describes a similar circuit of the heavens with respect to the stars—in the figure it is LNQDL, inclined at 5° to the ecliptic. A total eclipse of the sun (or of the moon) is, therefore, only possible if both the sun and moon happen to be in the neighbourhood of N or of D (the "nodes"). For example, if the moon is in that part of the heavens represented by the point Q, and the sun is at R, the angular separation of Q and R is 5°, so that the discs of the sun and moon are well apart, and an eclipse, total or partial, is clearly impossible. But the inclination of the two planes is not the only element that introduces complexity into the prediction of eclipses. The moon's orbit around the earth, due to the controlling influence of the latter alone, is an ellipse, but owing to the sun's gravitational attraction the orbit undergoes certain changes or perturbations; the only one which need concern us here is the slow backward movement of the nodes N and D along the ecliptic (shown by the arrows in Figure 42). The plane of the moon's orbit is thus, as it were, slipping gradually backwards, the period of a complete cycle of a node round the ecliptic being nearly nineteen years. Relatively to the earth the sun appears to describe the complete cycle of the ecliptic (in the direction NRD) in a year, but owing to the backward movement of the nodes the interval between two consecutive coincidences of the sun with a node (say N) will be less than a year—it is found to be 346·62 days, a period called an eclipse year. Nineteen of such periods are equivalent to 6585·78 days. The average interval between two successive new moons—a period

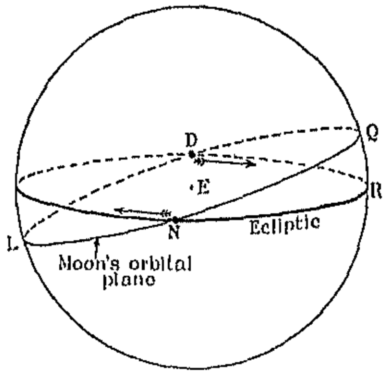



FIG. 42.

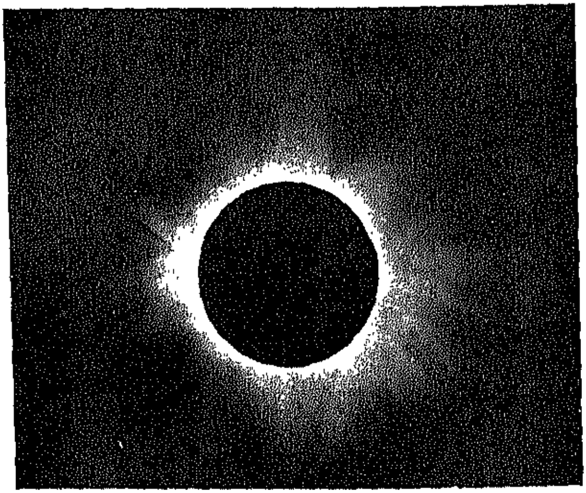
called a lunation—is 29·53 days, and 223 lunations are equal to 6585·32 days, which is almost equal to the value of nineteen eclipse years. The importance of this relationship between the eclipse year and a lunation is this: if at a particular new moon the sun is in the neighbourhood of a node so that a solar eclipse is taking place, then after 6585·32 days it will once more be new moon, and the sun will again be in the neighbourhood of the node and therefore another solar eclipse will occur. This period of recurrence of eclipses—the preceding argument holds clearly for lunar eclipses as well—of 6585·32 days, or eighteen years eleven days, called the Saros, was known (as we have seen) to the ancient Chaldean astronomers. The accurate prediction of all the circumstances of an eclipse of the sun is a matter of intricate calculation. The fundamental requirements are an accurate knowledge of the movements of the moon and the sun relatively to the earth. If these are known, the beginning and end of totality (if the eclipse is a total solar eclipse), the narrow strip on the earth's surface from which the eclipse is seen total, the percentage of the sun's disc covered by the moon at places outside the zone of totality, all these can be calculated with great accuracy. Under the most favourable combination of circumstances, an eclipse of the sun can be total for seven minutes fifty-eight seconds.

Despite the utmost refinements of modern astronomical science, the beginning of totality is uncertain to the extent of several seconds of time; the commencement of the total solar eclipse of June 29, 1927, which was visible in northern Wales, northern England, and in Scandinavia was estimated to be about two seconds before the predicted time; the Sumatra eclipse of 1926 was two seconds late, and the American eclipse of 1925 was five seconds late. What are the causes responsible for this lack of agreement between observation and prediction? The prediction of recent eclipses is based on Professor E. W. Brown's *Tables of the Moon*, a monumental work which takes account completely of the gravitational effect of every body of the solar system on the motion of the moon. The discrepancy between observation and prediction calls, therefore, for explanation in terms of circumstances or processes outside those associated with Newton's general law of gravitation. One such explanation is in terms of the non-uniformity of the earth's

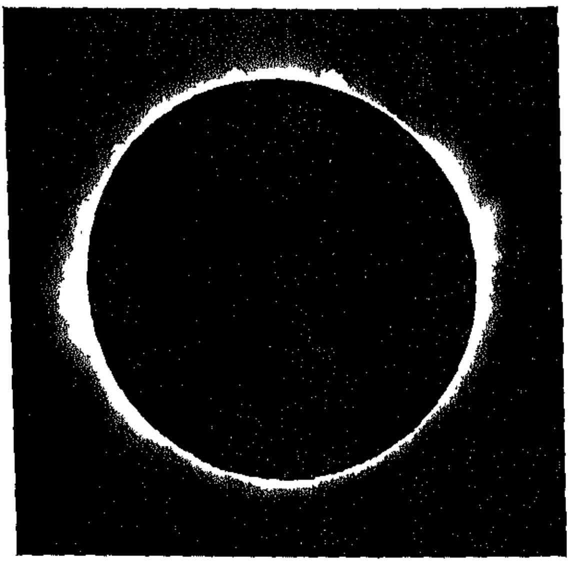
rotation, the effect of which would be most clearly marked in the predicted movements of the moon. To illustrate this, let us take an extreme example. We shall suppose that the positions of the moon are observed with every refinement during two intervals, measured by the complete rotation of the earth with reference to the fixed stars; further, we shall suppose that in the second interval the rotation of the earth has been slowed down in comparison with the rotation in the first interval, so that the second interval is actually a little larger than the first. The observations of the moon will show that it has moved a little more in the second interval than in the first, let us say, as a concrete case, 13° as against 12°. Now the period of rotation of the earth with respect to the stars is the fundamental unit of time, which we generally regard as invariable; the earth is, in fact, our standard clock. If we believe that all the rotational periods of the earth are the same, then, in our illustration, the observations appear to indicate that the moon is behaving in some inexplicable way, for at the end of the second interval it is 1° ahead of its proper place in the heavens. Now this is precisely what is found when the observed positions of the moon (and, in a lesser degree, the sun and the inner planets) are confronted with the predicted positions based essentially on the non-variability of the earth's rotation (a qualification to this statement will be noted later). The differences are extremely minute, but in the case of the moon they are nevertheless trustworthy. The inference is that the rotational period of the earth is not quite constant. Now one cause of the variability of the earth's rotation has been traced by Professor G. I. Taylor and Dr. H. Jeffreys to the friction, tending to retard rotation, due to tides in shallow seas. It is interesting to note that the Bering Sea is as efficient, in this respect, as all the remaining seas put together. The effect of tidal friction, although minute—it is estimated that, due to this cause, the day has been lengthened by a second in about 120,000 years—is, nevertheless, real and demonstrable. Due allowance is therefore made for minute changes due to tidal friction in the predicted positions of the moon. But when this is done certain small discordances in the position of our satellite remain, with the result that astronomers are unable to predict—even a few months in advance—the accurate

position of the moon at a particular instant; consequently, they cannot predict with absolute accuracy the beginning or end of a total solar eclipse. The errors of prediction, as we have seen for the eclipses of 1925–1927, are indeed small, but nevertheless they demand an explanation. It is a well-known principle in dynamics that if the matter, of which a rotating body such as the earth is composed, is distributed in a different way, the rotational period is altered. Terrestrial phenomena, such as large-scale earthquakes, for example, can cause such changes in distribution. Professor Brown has estimated that a gradual and uniform expansion of the earth corresponding to the general elevation of the surface by about 2 inches would provide a slowing up of the earth's rotation, which would account for the observed discrepancies in the moon's movements during the last 120 years. An interesting suggestion has been made very recently that a similar slowing up of the earth's rotation could be explained by the gradual addition of melted polar ice to the oceans; it is estimated that the gradual transference (during the last 120 years) of a thickness of about 20 feet of the polar ice caps would result in the general deepening of the seas by about 2 inches. The reader may imagine that we are now sailing before the wind on the uncharted sea of speculation; but he must remember firstly that the very minute but puzzling discrepancies between the moon's observed and predicted positions are definitely established, and secondly that the processes of nature, to which reference has been made, are not improbable and certainly not impossible.

To the onlooker a total eclipse of the sun presents a rapid succession of astonishing and awe-inspiring phenomena. A few minutes before the beginning of totality, when all but a thin crescent of the sun is covered by the moon, shadow bands are seen racing and dancing on the ground; these are due to rapidly-varying conditions in the earth's atmosphere. The onrush of the moon's shadow—" the onrush of rapidly-spreading and engulfing darkness," as one writer describes it—is probably the most awe-inspiring experience that nature has to offer. There is to the spectator the sense of utter impotency in the face of a darkness that hurls itself along with a speed outside the range of common experience. When the advancing moon has just covered up the last visible crescent of the solar disc,



(*a*) Corona, January 14th, 1926.
*Royal Observatory, Greenwich.*



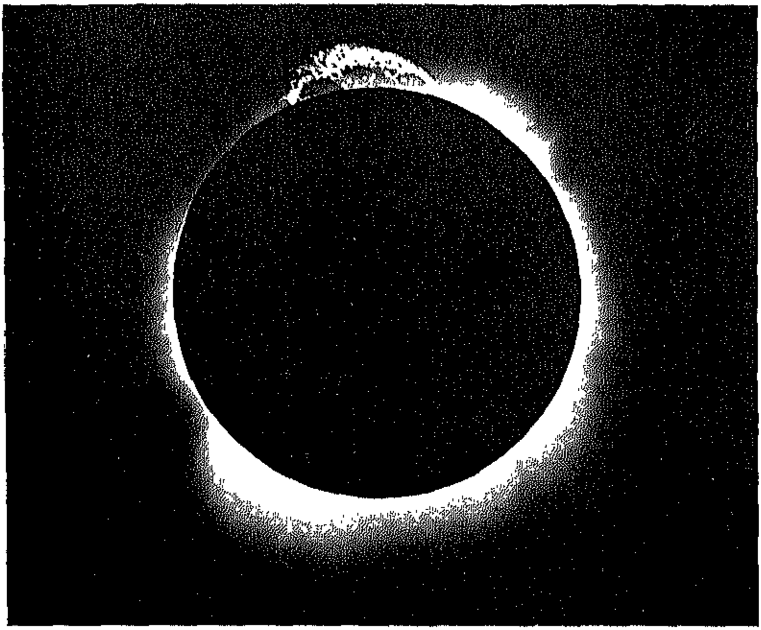
(*b*) Corona, June 29th, 1927.
*Royal Observatory, Greenwich.*

bright specks of light flash out on the eastern limb for an instant—these are "Baily's beads," due to the irregularities on the moon's surface, the deeper valleys allowing the passage of the last rays of sunlight just before the commencement of totality. At once the chief feature of the eclipse flashes into view—the corona—pearly white and mystical, a huge solar envelope of surpassing beauty that fascinates throughout the entire period of totality. Totality ends, the corona vanishes, the darkness quickly lightens, the moon rapidly uncovers the western limb of the sun, until eventually the sun shines forth in all its undimmed splendour; the eclipse is over and human experience has been enriched by the most sublime spectacle in the whole realm of nature. Plate V shows the corona at the eclipse of January 14, 1926, and the inner corona at the eclipse of June 29, 1927.

Frequently the spectator is rewarded during totality with a view of one or more *prominences*—pink-red protuberances of diverse sizes and forms—extending from the dark circle of the moon. It is rather strange that previous to the eclipse of 1842, visible in central and southern Europe, there is no record of their having been seen before. Of this eclipse, Francis Baily, who observed it in Italy, wrote: "But the most remarkable circumstance attending the phenomenon was the appearance of three large protuberances, in colour red, tinged with lilac and purple." According to Baily the height to which they extended above the solar disc was estimated to be 54,000 miles. In Plate VI (*a*) is a photograph of the large prominence visible at the eclipse of May 29, 1919; this photograph was taken by Professor Eddington, who was stationed on the island of Principe, off the west coast of Africa. As we shall see in the next chapter, we do not require to wait for a total eclipse to study the solar prominences; in these days the photography of prominences is a matter of routine in any solar-physics observatory. The history of this great prominence could then be studied from the available photographic records. Its first appearance was noted on March 22, 1919; thereafter it gradually increased in height and intensity. On the morning of the eclipse its form began to alter greatly. It appeared to be connected by long streamers to a sun-spot, and a little later it was seen to detach itself from the solar disc. In a little less

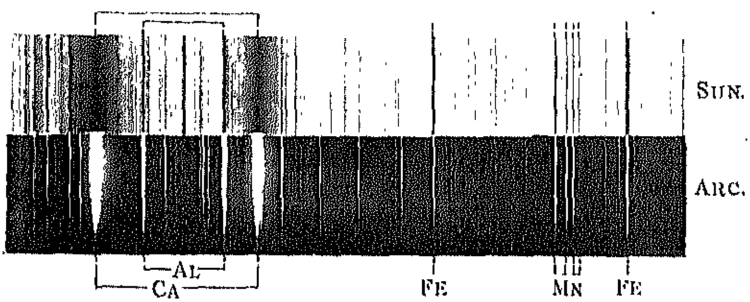
than seven hours it had risen from a height of 120,000 miles above the solar surface to 400,000 miles at a speed varying between 4 and 40 miles per second. Thereafter it gradually faded away. A few weeks later, a second great prominence developed. On July 1 it was comparatively insignificant, but a fortnight later it increased to an enormous extent, reaching a maximum height of 500,000 miles; the velocity of ascent varied between 20 and 100 miles per second. A more detailed account of prominences—vast solar eruptions, as they undoubtedly are—must be postponed to the succeeding chapter.

It has long been known that the form and brilliancy of the corona varies according to the state of activity of the sun. At sun-spot maximum the coronal light is fairly regularly distributed around the sun; at sun-spot minimum the extensions in solar equatorial regions, together with polar plumes, are conspicuous. Between sun-spot minimum and maximum there is the "square" or "intermediate" type of corona with no marked extension in equatorial or polar regions, but with streamers generally found in middle latitudes. It is not surprising that the brilliancy of the corona is also found to vary from one eclipse to another. Very little accurate work has been done in this connection, but the available evidence seems to indicate that the total coronal light is but a very small fraction of the total light of the full moon. Again, there appears to be a general correlation between coronal forms and prominence phenomena. Unlike sun-spots, prominences are not limited to definite zones of solar latitude, and it is a matter of observation that the maximum or intermediate types of corona are never associated with the appearance of prominences in high latitudes. The exact physical relation between the various coronal forms and the corresponding sun-spot and prominence phenomena are not yet fully understood. Progress in this department of astronomy must necessarily be slow, for the corona is an elusive object, revealing itself only for about two minutes, on the average, per annum.



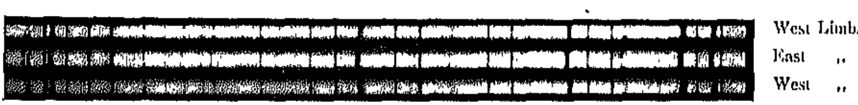
(*a*) Prominence, May 29th, 1919.

*Prof. A. S. Eddington.*




(*b*) Spectrum of the Sun with comparison arc spectrum.

*Mr. C. P. Butler.*




(*c*) Spectra of East and West Limbs of the Sun.

*Mt. Wilson Observatory.*

# CHAPTER VI

## THE SPECTROSCOPE AND SOLAR PHYSICS

IN 1666, Newton established the fact that sunlight is a blend of many colours, ranging from red to violet. We are all familiar with the colours of the rainbow, in which red merges into orange, orange into yellow, and so on; it is the raindrops that have effected the decomposition of the sunlight into the well-known variegated hues. More common—in these days of motor-cars—is the optical phenomenon seen on every road

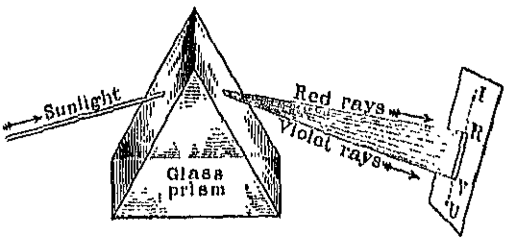



FIG. 43.

after a shower of rain; a drop of oil has spread into a thin film, from which proceed in concentric rings the familiar rainbow colours. A prism of glass achieves a similar result, as Newton demonstrated. A beam of sunlight admitted through a small aperture in a screened window falls on the side of a prism, as illustrated in Figure 43. The sunlight is split up into the prismatic colours, and if a sheet of paper is held at right angles to the emerging beam, a narrow strip RV will exhibit the succession of the rainbow colours. In its passage through the glass the violet constituent of sunlight has been refracted more than the red constituent. The strip of coloured light RV in Figure 43 is called a *spectrum*. In 1802, Wollaston, performing a similar experiment by admitting sunlight through a thin rectangular aperture (a slit), noticed that the solar

spectrum was crossed (at right angles to the direction of the strip) by seven thin dark lines. Twelve years later, Fraunhofer, using a much narrower slit and observing the spectrum by means of a telescope, counted no less than 574 dark lines, some barely visible and others strongly marked. Fraunhofer succeeded in mapping out these lines; to the more prominent he assigned letters, which are in use to this day.

The total radiation of the sun is not restricted to the visible spectrum between red and violet. To these colours the eye is sensitive, but owing to the limitations imposed by its optical and physiological properties the eye is blind to rays outside this range. That such rays exist was demonstrated at the beginning of last century. If a bulb of a thermometer is held at various parts of the visible spectrum it is found that the heating effect of the spectrum rays is very slight at the violet

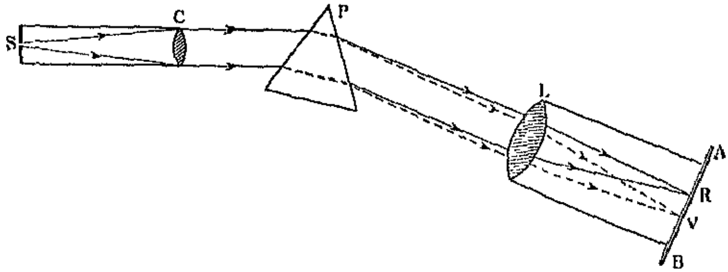



FIG. 44.—THE SPECTROSCOPE.

end, increasing gradually towards the red. If the bulb is moved gradually beyond the red end (between R and I in Figure 43) the thermometer rises very markedly, thus proving that there are invisible heat rays outside the range of appreciation by the optical mechanism of the eye. This region of the spectrum is called the *infra-red*. The existence of rays beyond the violet end of the visible spectrum can be demonstrated by their effect on a photographic plate placed beyond V (between V and U in Figure 43). This is the region known as the *ultra-violet*. The visible spectrum represents, then, only a portion of the radiation from the sun.

The instrument employed in the study of a spectrum is called the spectroscope; the simple principles of its design are illustrated in Figure 44. The light from the sun or any

other source is admitted through a narrow slit S, placed in the focal plane of a lens C (or combination of lenses); the function of C is to convert the light emerging from C into a parallel beam. This beam falls on the face of the prism P, which splits the light up into its constituent prismatic colours, all the rays of the same colour being deviated by the same amount. In the figure only the red and violet rays are shown—the former with a full line, the latter with a broken line. After emerging from the prism the rays enter the object glass L of a telescope and are brought to a focus—the red light at R and the violet at V—where they may be viewed by means of a telescopic eye-piece or photographed on a plate AB. The angular separation of the red and violet rays can be greatly increased by using a series of prisms. The spectroscope can be attached to a telescope with the slit S in the focal plane of the telescope's object glass or mirror; the latter simply acts as a collector of light from the source under consideration—a star, for example. The light then passes through the slit S into the spectroscope, and the spectrum is formed in the way just indicated. A diffraction grating may be used instead of a prism, and for particular purposes a quartz prism or series of such prisms is employed. Whatever the apparatus, the general principles of making a visual observation or obtaining a photographic record of the spectrum under consideration are essentially illustrated in Figure 44.

We describe now the laboratory experiments with the spectroscope which led Kirchhoff to formulate the laws of spectrum analysis which, when applied to the sun and stars, opened up a vast field of research and extended, and still extends, astronomical knowledge in the most amazing way. Terrestrial substances can be rendered incandescent in various ways and their light examined, as a spectrum, by means of the spectroscope. If a small amount of common salt (sodium chloride) is held in an ordinary flame the rich yellow light characteristic of sodium will be observed; a salt of strontium will similarly yield the emission of the brilliant red light familiar in fireworks. Much higher temperatures are necessary for the vaporisation and luminescence of such elements as iron and aluminium. We do not propose to enter into a technical discussion as to the manner in which the stimulation of the light

or radiation characteristic of the various terrestrial substance is achieved; it is perhaps sufficient to mention, in the order of increasing temperature, the electric furnace (about 1700° Centigrade), the electric arc (about 2800° C.), and the electric spark, in which still higher temperatures are reached. Gases are studied under very low pressure in vacuum tubes; an electric discharge through the tube renders the gas in the tube incandescent.

Kirchhoff found that when a solid such as lime was heated to incandescence and the light examined in the spectroscope, the spectrum was a rainbow spectrum with the succession of colours from red to violet without the least suspicion of dark lines such as are observed in the solar spectrum. Such a spectrum is called a *continuous spectrum.*

When a few particles of a salt of sodium were placed on the wick of a spirit lamp and the characteristic light examined in

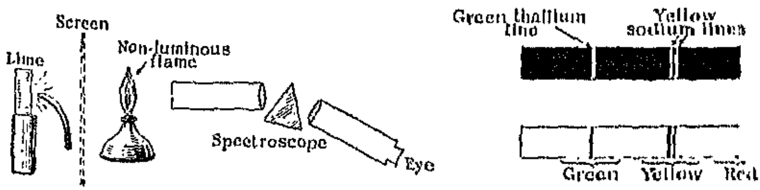



FIG. 45.

the spectroscope, it was found that the spectrum consisted simply of two *bright* yellow lines, and no matter how the experiment was varied these two bright lines were invariable in position. Similarly, the spectrum of thallium consisted principally of a bright green line. Later spectroscopic work shows that the arc spectrum of iron consists of thousands of bright lines of varying intensity and distribution and invariable in position. Whatever the metal or substance, the spectrum consists of characteristic bright lines, with no background of continuous spectrum. Such a spectrum is called a *bright line spectrum.*

A further experiment of the utmost significance is illustrated in Figure 45.

A block of lime is rendered luminous by appropriate means. Between the lime and the slit is placed a lamp (with a non-luminous flame), on the wick of which are placed particles of

a salt of sodium and a salt of thallium. A screen can be put into position to block out the light from the lime; accordingly, the spectrum, as viewed at the eye-end of the spectroscope, consists of the two bright yellow lines of sodium and the bright green line of thallium. When the screen is removed so that the light from the incandescent lime is also allowed to enter the slit of the spectroscope, an amazing change is observed. The brilliantly-coloured continuous spectrum—due to the incandescent lime—flashes into view, but the bright lines of sodium and thallium are instantly replaced by *dark* lines, occupying precisely the same positions in which the corresponding bright lines had been previously seen. It is to be noted that the source giving rise to the continuous spectrum, *i.e.* the lime, is at a higher temperature than that of the sodium and thallium vapours. The spectrum, which we have just described, consisting of the continuous spectrum crossed by dark lines is called an *absorption spectrum*—the light of the continuous spectrum is absorbed by the intervening cooler substances at precisely those places at which the bright lines due to these substances appear. But the absorption lines although dark are not destitute of light. They are dark only by contrast with the adjacent brilliant continuous spectrum; the sodium and the thallium vaporised in the flame of the lamp are still emitting yellow and green light, as well as engaging in the process of selective absorption of the continuous spectrum.

We shall now summarise the above spectrum phenomena.

(1) A bright line spectrum is given by an incandescent gas under low pressure, or by the vapours of an element volatilised at high temperature. Every chemical element gives its own characteristic bright line spectrum, each line occupying a definite position in the spectrum.

(2) When the light from a source which produces a continuous spectrum passes through a gas or vapour whose temperature is lower than that of the source, the cooler gas or vapour absorbs from the continuous spectrum precisely those rays which characterise its own spectrum; the resulting spectrum is an absorption spectrum.

It may be added that chemical compounds which remain undissociated when excited to luminescence produce a spectrum

consisting of one or more bright bands; in accordance with (2), such compounds can absorb light from the continuous spectrum—the dark bands are then called absorption bands. The name *emission spectrum* is given to a spectrum which consists of one or more of the following: continuous, bright-line or banded spectra.

The principles underlying the production of spectra are the starting-point for the investigation of the chemical constitution of the sun and stars, and of the physical conditions under which matter exists in these bodies. Confining our attention to the sun, we remind the reader that the solar spectrum consists of a bright continuous spectrum crossed by a very large number of dark lines. The dark absorption lines in the solar spectrum are the evidence of gases or vapours at a lower temperature than the photosphere, forming an atmosphere through which the intense photospheric radiation which produces the continuous spectrum has to pass antecedent to its final escape into space. The gases and vapours which are thus responsible for the appearance of the absorption lines in the solar spectrum form what is called the reversing layer, which, as was mentioned in the previous chapter, is a comparatively shallow stratum extending but a few hundred miles above the photosphere. The chromosphere, which is a much more extensive but more tenuous atmosphere, consists of but a few elements, which of course absorb the photospheric radiation according to their own characteristic properties. But the main point is that the absorption lines of the solar spectrum are, on the whole, due to the gases and vapours of the shallow reversing layer. Now iron, volatilised in the electric arc, has its own characteristic bright-line spectrum. If in the solar spectrum we can pick out from its thousands of dark lines the exact counterparts, as far as position in the spectrum is concerned, of the numerous iron lines, then we must conclude that the vapours of iron are present in the reversing layer of the sun. The identification of lines in the solar spectrum with the lines in laboratory spectra of the chemical elements constitutes what may be described as the chemical analysis of the sun, or more precisely, of the sun's reversing layer. Plate VI (*b*) illustrates more clearly than verbal description can achieve the process of identification of the

solar lines with the lines characteristic of certain terrestrial elements. The upper spectrum is a portion of the solar spectrum; the sunlight has been admitted through the upper half of the slit of a spectroscope and a photographic plate records the features of the spectrum. Without removing the plate or altering the spectroscope in any way, light from an electric arc in which are the elements calcium (Ca), iron (Fe), manganese (Mn), and aluminium (Al) is admitted through the lower half of the slit; the bright lines due to these elements are photographed on the same plate in a strip below that which shows the solar spectrum. A positive is made of the photograph, and Plate VI (*b*) is a copy of part of it. Certain groups of lines which are known to belong to the arc spectra of the elements concerned are marked appropriately in Plate VI (*b*), together with their dark-line counterparts in the solar spectrum. Worthy of notice are the two intensely bright lines due to calcium (Ca) in the arc spectrum with the wide and very dark lines opposite in the solar spectrum; these are the H and K lines of calcium in the violet end of the spectrum. In this way no less than sixty-six of the terrestrial elements have been identified up to the present in the sun—mostly in the reversing layer.

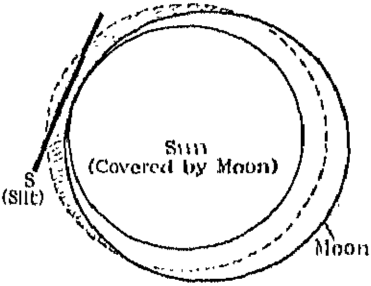


FIG. 46.

The existence of an outer atmospheric shell surrounding the sun has been inferred, as we have seen, as a consequence of the presence of the dark absorption lines in the solar spectrum. Are there any means whereby the reversing layer and the chromosphere—presumably at a very high temperature—may be allowed to give their own characteristic bright-line spectrum? The answer is that a total eclipse of the sun affords such an opportunity. As the moon creeps gradually over the disc of the sun there comes the instant when the diminishing crescent of the sun suddenly vanishes and totality begins. At this instant, a part of the solar atmosphere, in the form of a crescent, is not yet covered by the black disc of the moon; this is illustrated in Figure 46,

the dotted line representing the upper level of the chromosphere, and the shaded crescent that portion of the solar atmosphere not covered up by the moon at the beginning of totality. Now if a spectroscope is arranged in such a way that the slit receives light from a cross-section of the crescent as at S, the spectrum will be a bright-line spectrum, for there is now no question of the absorption of the photospheric radiation, as the photosphere is entirely covered by the moon at this instant.

The emission spectrum of the reversing layer and chromosphere obtained in this way is called the *flash spectrum*, so called because just before totality, when a crescent of the photosphere is still visible, the spectrum is crossed in the usual manner by the dark absorption lines, and then at the instant of the beginning of totality the whole character of the spectrum alters; suddenly in place of the dark lines flash out the bright lines of the solar atmospheric shell. From the photographic record of the flash spectrum the heights to which the various constituents of the solar atmosphere extend are deduced from the lengths of the spectrum lines. As might be expected from terrestrial analogies, the two lightest elements known—hydrogen and helium—are found high up in the chromosphere, but the most astonishing feature is the presence of calcium vapour at the highest chromospheric levels, for calcium is a comparatively heavy element. We shall have occasion later on to refer in greater detail to this apparently perplexing phenomenon, the calcium chromosphere.

Before proceeding to describe the modern achievements of the spectroscope in the domain of solar physics, it is necessary to give a brief account of the relations between the production of spectra and the conceptions introduced by modern atomic physics. When a stone is dropped into a still pond, surface waves spread outwards in ever-increasing circles. The distance between the crests of two successive waves is called the *wave-length*, the speed at which the wave travels the *wave-velocity*, and the number of waves passing per second through any particular point the *wave-frequency*, or simply the frequency; it is clear that if the wave-length and velocity are known the frequency can be calculated immediately. Now, according to the electro-magnetic theory of Maxwell, light is propagated in

very much the same way with a velocity—in space void of matter—of 186,000 miles per second, and this velocity is the same whatever the nature of the light. Wave propagation requires a medium—in our illustration it is the water of the pond—and so in the propagation of light waves a medium called the ether is hypothecated. Now wave-motion, whether it be the surface waves of the pond or etheric light waves from a radiating source, is characterised by the wave-length and the wave-velocity (or by one of these and the frequency). As regards light—and other electro-magnetic waves—the difference between two kinds of light, for example red light and blue light, is simply due to the difference between the wave-lengths of the two kinds of light, for the other characteristic (the wave-velocity) is the same for both. When we examine the light of the incandescent vapour of iron in the spectroscope, we find that the prism has separated the light radiated by the iron into a definite number of components, some red, some yellow, and so on. The character of any particular line in the iron spectrum consequently depends on its wave-length, and with laboratory apparatus this wave-length can be measured. Just as every private in a British regiment is "named" uniquely by means of a number assigned to him and to no one else, so the multitude of lines in the iron spectrum are "named" according to their characteristic wave-lengths. The iron spectrum may then be regarded as a standard wave-length scale with which the lines in other spectra may be compared and by means of which accurate measures of the wave-lengths of these lines may be made. For example, Plate VI (*b*) exhibits part of the solar spectrum and part of the iron arc spectrum; from the known wave-lengths of the iron lines the wave-lengths of the solar lines may be found. It is found that the wave-lengths associated with light are exceedingly minute, and our ordinary standards of length are ill-adapted for spectroscopic purposes. The scientific unit of length is the metre—a little over 39 inches—and the unit of length adopted for the measurement of wave-lengths is a ten-thousand-millionth part of a metre; this unit is called an "angstrom unit," and in terms of this unit a wave-length is expressed thus, 6438A. The visible spectrum consists of light ranging from wave-lengths about 3900A in the violet to about 7600A in the red.

But the visible spectrum represents only a very small portion of the range of wave-lengths covered by atomic radiations or electro-magnetic manifestations now almost completely explored by physicists. The diagram in Figure 47 illustrates the relation of the visible spectrum to the range of wave-lengths of these other radiations; for the shorter wave-lengths the angstrom unit (A) is used, and for the longer wave-lengths the centimetre (cm.) and metre (m.). (Figure 47.)

We recall that the infra-red is the region of heat radiations, the ultra-violet that of radiation with actinic properties, and we shall see in a later part of the book that even the shorter wave-lengths to the left of the ultra-violet in the diagram are of astronomical importance.

The smallest particle of an element that can take part in a chemical action is called an atom, and the diversity of the chemical and physical characteristics of elements such as

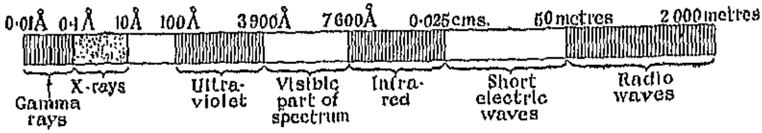



FIG. 47.

hydrogen and iron is traced to the differences of atomic structures. A far-reaching discovery towards the elucidation of the structure of the atom was made by Sir J. J. Thomson, who established the existence of minute carriers of negative electricity—called *electrons*—common to all atoms investigated. Each electron carries the same electric charge—the unit of negative charge. The later researches of physicists led to the conception known as the Rutherford-Bohr model. The atom is conceived as a miniature solar system, a number of electrons (the number depending on the particular element) circulating around a nucleus in planet-like orbits. The nucleus is itself a complicated structure—very minute as compared with the dimensions of the electronic orbits—consisting of *protons*, each with a unit charge of positive electricity, and, generally, of a number of electrons, referred to as the nuclear electrons to distinguish them from the orbital or planetary electrons. In the solar system the force controlling the planets is the force of gravitation; in the atom it is the electrical attraction

between the positively charged nucleus and the negatively charged planetary electrons. The mass of the atom is almost wholly concentrated in the protons of the nucleus, for the mass of a proton is about 1800 times that of an electron. Matter, then, is built up of two fundamental entities, the proton and the electron. Now matter in its ordinary state is electrically neutral, that is to say, that if an atom is built up of a certain number of electrons—planetary and nuclear—its nucleus must have the same number of positive charges, that is, the same number of protons. The masses of the atoms of chemical elements are determined by the number of protons in the atomic nucleus. The simplest atom is that of hydrogen—the lightest of all the elements—which consists of one proton (the nucleus) and one revolving electron. The next lightest and simplest atom is that of helium, four times the mass of the

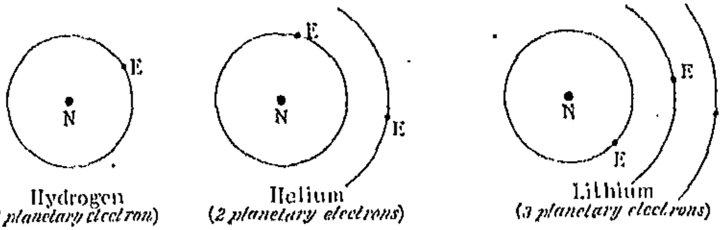



FIG. 48.

hydrogen atom, with two planetary electrons; its nucleus consists of four protons and two nuclear electrons. The atom of sodium has 11 electrons revolving around a nucleus built up of 23 protons and 12 nuclear electrons. To each element is assigned a number—the *atomic number*—which is equivalent to the number of planetary electrons in the atom under normal conditions. (This reference to "normal conditions" may appear somewhat vague, but we shall see that atoms under certain conditions of temperature and pressure can lose one or more of the planetary electrons.) A relation which we may note here—its importance will be realised when we come to deal with the internal constitution of the stars—is that the atomic numbers of the elements, hydrogen excepted, are equal to, or very nearly equal to, half the number of protons in the atomic nuclei; for example, the atomic number of sodium is 11 and the number of protons in the sodium nucleus is

23. Figure 48, intended to be diagrammatic only, may assist the reader to visualise the structure of the atoms of hydrogen, helium and lithium; in the figure, N denotes the nucleus and E a planetary electron. Compared with the dimensions of the atom, *i.e.* with the dimensions of the outermost electronic orbit, the diameter of the nucleus is extremely minute—less than a hundred-thousandth part of the atomic diameter. The planetary orbit of an electron may be a circle or an ellipse and, unlike the orbits of the planets in the solar system, capable of surprising variations, as we shall see; another distinction is that the planes of the electronic orbits are generally widely dissimilar.

Such, in brief, is the modern conception of atomic structure. To interpret the phenomena associated with the solar radiation

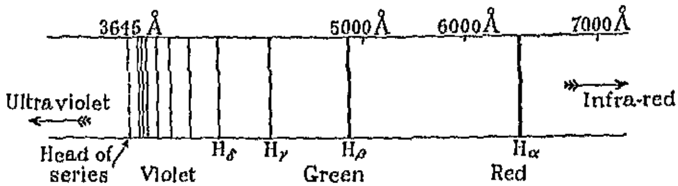



FIG. 49.

and its analysis by the spectroscope, we are led to the investigation of the properties of the atoms of the chemical elements. Let us consider the simplest atom, that of hydrogen. We have seen that the spectroscope reveals its presence in the sun; in the laboratory it can be made to glow in a vacuum tube and its emission spectrum can be photographed. Figure 49 is a diagram of the hydrogen spectrum mainly within the range of the visible spectrum. The spectrum is seen to consist of a series of bright lines—a red line, called $H_\alpha$, a green line $H_\beta$, and a succession of violet lines crowding closer and closer together, coming eventually to a dead halt, just within the ultra-violet, at the dotted line whose wave-length is 3645A. This does not represent the whole of tho hydrogen spectrum; two other series have been found, one in the infra-red and the other in the ultra-violet. We shall consider mainly, however, the Balmer series of hydrogen lines as illustrated in Figure 49. The lines are not arranged haphazardly, but according to a definite scheme, as was early realised, in which the number of

the line, counted from $H_\alpha$ towards the violet is related by a simple mathematical formula to the corresponding wave-length. Nature evidently regulates the radiation of the hydrogen light by some precise process. What is this process in relation to the model of the hydrogen atom described in the preceding pages? As it is reasonable to suppose that the emission or absorption of light by matter—that is, in the last resort, by an atom—must be caused by or must result in some change in the atom itself, a theory has been propounded in which such change is limited to the possible contraction or extension of the electronic orbit. The discontinuous character of the hydrogen spectrum (the Balmer series in Figure 49) suggests that the planetary electron can only move in certain well-defined orbits. In 1913, Professor Niels Bohr, of Copenhagen, succeeded in correlating the lines in the Balmer series with a series of orbits in which, and in no other, it was postulated


FIG. 50.

that the electron must move. A few of these orbits are shown diagrammatically in Figure 50. The relative radii are as the squares of the natural numbers; that is, if the radius of the innermost orbit is 1, the radius of orbit 2 is $2 \times 2$ or 4, the radius of orbit 3 is $3 \times 3$ or 9, and so on. The normal orbit of the electron is that numbered 1; the radius of this orbit is so minute that if an inch is divided into one thousand million equal parts the radius is about equal to two of these small divisions. The rapidity of the electron's motion in this orbit may be judged by the fact that it makes about a hundred million revolutions in one second. Just as the driving weight of a pile-driver is capable of being more effective the higher it is above the pile—the energy which can be applied in this instance is called potential energy—so the total amount of energy of the electron, due to its position relative to the nucleus and the energy of its orbital motion, varies from one orbit to another, increasing outwards from the nucleus. If the electron happens to be revolving in orbit number 4 and then jumps to

orbit number 3, its energy is diminished by a calculable amount. Bohr supposes that when this occurs the atom throws off this difference in energy as a *quantum* of radiation of a definite wave-length. If the electron jumps from orbit number 4 to orbit number 2, radiation of a different wave-length is emitted by the atom. Now let us consider what is supposed to occur when a small amount of hydrogen enclosed in a vacuum tube is stimulated into incandescence by electrical means. The atoms are, at first, in the normal state; that is, the electrons are all revolving about their respective nuclei in the lowest orbit, number 1. When the gas is made to glow, energy is being supplied to the atoms; the electrons jump to higher orbits, some to number 4, some to number 10, and so on. As if anxious to get rid of the energy supplied, they jump back to lower orbits; more energy is, as it were, pumped into the atoms, and the electrons again jump to higher orbits (not necessarily the same as regards the individual atom), and this double process is continued so long as the extraneous energy is being supplied. Bohr supposes that the fall of the electrons from orbits number 3 and higher back to number 2 results in the emission of radiation, which is evidenced in the Balmer series; the line $H_\alpha$, for example, is the result of an atom emitting radiation equivalent to the loss of energy represented by the fall of the electron from orbit number 3 to orbit number 2; and so on for the other lines of the series. The more intense the energy applied by the extraneous stimulating agent the higher the orbits to which some of the electrons will attain. In the laboratory the highest orbit attained so far is number 22, corresponding to the 20th line of the Balmer series; in eclipse photographs of the chromosphere in 1926, Col. F. J. M. Stratton and Mr. C. R. Davidson have observed the Balmer series up to line number 32 corresponding to the electronic orbit number 34. The radius of this latter orbit is accordingly about one thousand times the radius of the lowest orbit number 1; that is to say, the linear dimension of a hydrogen atom under the particular conditions of temperature and pressure in the chromosphere can be about one thousand times that of unstimulated, *i.e.* cold, hydrogen atoms. Now there is no reason why some atoms should not fall to orbit number 1 or to orbit number 3, and so on; Bohr's theory predicts the nature of the emission in

these cases. Falls to orbit number 1 produce a series of lines in the ultra-violet subsequently observed by Lyman; falls to orbit number 3 produce a series of lines in the infra-red, and these have been found by Paschen. The spectrum of hydrogen produced under the conditions described is a bright-line spectrum, and Bohr's theory explains successfully the relative positions of the lines observed.

The production of a continuous spectrum forms a more complicated problem. The continuous spectrum must be conceived as composed of all wave-lengths between the limits within which it is observed. We shall see later that the characteristics of the continuous spectrum vary from star to star—for one star the red end may be the most brilliant, for another the blue end may be most brilliant, and so on. It will be sufficient to state that the particular properties of a continuous spectrum are dependent on the physical conditions in the solar or stellar photosphere and are independent of chemical composition.

The absorption of radiation is regarded as a process analogous to that of emission, but in the reverse direction; that is to say, when an atom absorbs radiation the electron jumps from orbit number 2, say, to orbit number 3; in this instance the atom absorbs one quantum of light with the wave-length that of the line $H_\alpha$.

So far we have dealt with the simplest atom, but a similar process of emission and absorption is believed to hold for any atom however complicated its electronic structure may be; in these atoms the inner system of electrons is supposed to be comparatively stable and it is the outermost electron or electrons that swallow or disgorge the quanta of energy responsible for the absorption or emission spectra.

We have seen that the hydrogen atom may be distended, under the influence of temperature, to dimensions vastly in excess of the dimensions of the atom in its ordinary state; similarly, the outer electron of helium (which has two planetary electrons) may for the same reason find itself moving in an orbit at a great distance from the nucleus. Can this process go still further, so that the helium atom will be effectively bereft of this electron? The answer is in the affirmative. The helium atom has then a resemblance to the hydrogen atom, and the application of Bohr's theory leads to the prediction of certain

emission lines in its spectrum, which are different from the lines given by helium in the normal state. These lines can be produced in the laboratory, and they are observed also in the spectra of the hottest stars. The helium atom which has lost one electron is said to be *ionised*. As regards atoms with a more numerous retinue of planetary electrons, one or two or more electrons may be torn away from the normal atom; for example, using a powerful electrical discharge, Professor A. Fowler has succeeded in producing trebly-ionised silicon, that is, silicon which has had three outer electrons forcibly ejected from its normal array of electrons. In the interior of the sun or of a star where radiant energy is incomparably more intense than anything laboratory methods can produce, the process of ionisation is believed to be complete, or nearly so; the lighter atoms are stripped of all their electrons and reduced to bare nuclei; the heavier elements are left, at the most, with one or two of their inner electrons intact; possibly even these are torn away from the nuclei in the fierce heat of the solar or stellar furnace.

What we said as regards the spectra of helium and ionised helium is true of an element such as iron. The spectrum produced by iron atoms with all their array of electrons complete is distinct, and completely different, from the spectrum produced by iron atoms singly, doubly, etc., ionised. Again, the atoms of some elements are ionised with comparative ease, others with great difficulty; in terms of temperature this may be expressed by saying that more intense heat is required for the ionisation of some atoms than for others. But this is not all, for ionisation depends on another factor, namely, the pressure of the gaseous or volatilised element concerned. In a dense gas the expelled electrons are almost instantly recaptured by the ionised atoms, so that effectively the atoms must be regarded in their complete and undamaged (that is, normal) state.

Such are some of the concepts to which modern physics has introduced us. Before proceeding to a more detailed spectroscopic study of the sun we must make adequate reference to a general principle of the utmost importance in the interpretation of solar and stellar spectra. When we discussed the identification of certain lines in the sun's spectrum with the

numerous lines of the comparison spectrum of iron (Plate VI (*b*)) photographed with the same instrument on the same plate, the reader probably inferred that the coincidence of a particular line in the solar spectrum with its counterpart in the iron spectrum was always exact, and this inference may have been generalised still further to include all stellar spectra. But the inference has to be modified for the following reason. If the substance—let us consider iron—which is responsible for the lines in the solar spectrum is moving towards us, or, what is equivalent, we are moving relatively to the iron and towards it, it is clear that we shall meet per second more waves of any particular wave-length than if we and the iron were at rest relatively to each other. The result will be that the observed frequency will be somewhat greater, and it follows that the observed wave-length will be somewhat smaller. In these circumstances, all the iron lines of the celestial spectrum will appear to be not quite coincident with the corresponding lines in the comparison iron spectrum, but displaced slightly towards the violet end. Similarly, if the celestial source is moving away from us, the displacement will be towards the red end of the spectrum. If the displacement is measured, the velocity of the source towards us or away from us—this is known as the line-of-sight velocity or as the *radial velocity*—can be deduced as so many miles or kilometres per second. This remarkable principle is known as Doppler's Principle.

The application of Doppler's Principle, which we shall consider here, has reference to the rotation of the sun, the simplest evidence of which is found in the motion of sun-spots from the east limb towards the west. If we examine spectroscopically the solar light which emanates from a small area on the eastern limb, it is clear that we are dealing with a source which is moving towards us; similarly, the western limb is receding from us. In each instance the velocities at the limbs are due to the solar rotation, it being assumed that the sun as a whole and the earth have no motion towards each other; that is to say, that the earth's distance from the sun is constant. At the centre of the disc the rotation is responsible for a motion at right angles to the line of sight, and therefore a small area of the solar surface at the centre of the disc will have no radial velocity. The spectra obtained by placing the slit first on the eastern

limb of the sun and then on the centre of the disc will con
quently show that the lines of the former spectrum are
placed towards the violet with regard to the lines of the latt
The measurement of the displacement leads to the line-of-sig
velocity, in miles or kilometres per second, of that part of
limb concerned. We know the radius of the sun in mil
we are therefore able to calculate the rotational period c
responding to the solar latitude of the area examined. As
have seen in the previous chapter, sun-spots occur only
limited zones of latitude, so that our knowledge—derived fr
sun-spot observations—of how the rotational period vari
according to latitude is limited to the sun-spot latitudes. Tl
spectroscopic method is applicable to all solar latitudes, a
by it a complete knowledge of the rotational period of tl
surface layers from the solar equator to the poles is gaine
Plate VI (*c*) shows the spectra of the east and west limbs of tl
sun in which the relative displacement of the lines is clearl
exhibited.

The spectrum of the solar prominences—the vast gaseou
projections above the atmospheric layers—was first examine
at the eclipse of 1868 and found to consist of bright lines, o
which the hydrogen lines were the most conspicuous. A
prominent bright line near the position occupied by the yellow
line of sodium suggested the presence in the solar prominence
of a gas hitherto unknown on the earth. This gas was name
helium, and it was later identified by Sir William Ramsay
(in 1895) with a gas liberated from certain rare minerals. The
conspicuous H and K lines of calcium, in the violet, are also
found in spectra of prominences. The great brilliance of the
prominence lines suggested to Jansen and Lockyer, almost
simultaneously, the possibility of observing prominences at
any time during the day. The principle of the method is as
follows. In Figure 51, let the circle represent the image of
the solar disc formed in the focal plane of the telescope. If the
slit of a spectroscope is placed tangentially to the limb, as in
the figure, and over a prominence, the light entering the slit
will consist of diffused sunlight, together with the light from
the prominence. The observed spectrum will, therefore, consist
of the bright-line prominence spectrum superimposed on the
relatively faint continuous and dark-line spectrum of the

sunlight. If we limit our attention to the brilliant red line of hydrogen ($H_\alpha$), we remark that this line is simply the image of the narrow section of the prominence covered by the slit. By opening the slit wider, a view of a considerable part of the prominence or of the whole of it will be obtained in the red light of $H_\alpha$. By examining the complete circumference of the solar disc in this way, the forms of all the prominences can be studied. But this visual method of observation has its obvious disadvantages, especially as regards the eruptive prominences, the form and structure of which may be altering during the course of a few minutes with astounding rapidity. About 1890, Dr. G. E. Hale and M. Deslandres independently devised an instrument, called the spectroheliograph, which records photographically the solar prominences and renders possible a continuous study of their varying activities. In addition to the telescope (or its equivalent) which forms the image of the solar disc, and the slit which admits the light from a narrow strip of the object to be examined, and the prism or prisms which resolve this light into a bright-line spectrum, the instrument includes a second slit, which is placed in such a way that only the light from a particular line passes through to imprint its image on a photographic plate. The image on the plate is then the image of the narrow strip of the prominence covered by the first slit. If, then, the telescope is moved slightly so that an adjacent strip of prominence is covered by the first slit, and if in addition the photographic plate receives a corresponding shift, the two adjacent strips of the promience will be photographed side by side on the photographic plate. By a continuous movement of this kind the complete image of the prominence can be built up on the plate. We do not stop to consider the mechanical difficulties encountered in the construction of the spectroheliograph nor to describe the instrument itself in greater detail. It was soon realised that the instrument possessed potentialities of far-reaching significance.

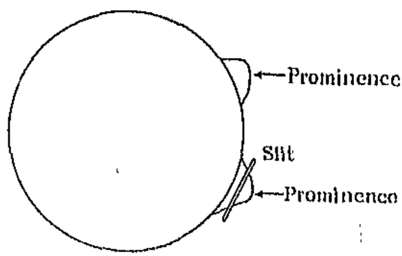


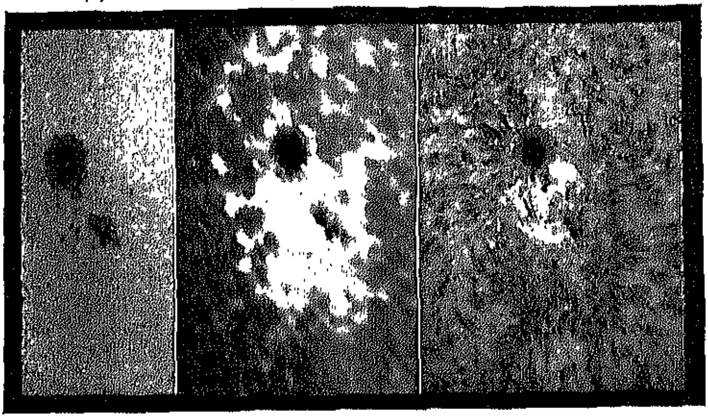

Fig. 51.

The dark lines of the solar spectrum are dark only by contrast with the brilliance of the adjacent continuous spectrum. Moreover, several of the so-called dark lines are found on closer inspection to have a more complicated structure than a first glance suggests. For example, the broad dark H and K lines of ionised calcium—due to calcium atoms which have lost one electron—have superimposed centrally a narrow bright emission line down the centre of which runs a narrow dark line. The interpretation of this complicated line-structure is that ionised calcium exists in the sun's atmosphere in three layers; the broad dark lines are due to the absorption of the photospheric light by atoms on the lowest levels; above this is a stratum of luminous calcium vapour responsible for the central emission line, and still higher is a cooler calcium atmosphere of feeble density responsible for the thin central absorption line. Suppose now that the slits of the spectroheliograph are longer than the image of the solar disc and that, for example, the second slit is set to admit only the light of wave-length corresponding to the emission section of the calcium K line. The instrument then builds up, in the way described, a picture of the sun's surface corresponding to the atmospheric level at which ionised calcium is responsible for the bright line. In a similar way the distribution of ionised calcium at different atmospheric levels of the sun—in the reversing layer, in the chromosphere and in the prominences—and the distribution of hydrogen are obtained. The photographs in Plate VII (*b*), (*c*) show the distribution of ionised calcium and the distribution of hydrogen in the chromosphere for a part of the sun on a particular day; the first photograph (*a*) is an ordinary photograph of the same part of the solar disc. The luminous clouds of calcium are called *flocculi*. As the photograph shows, they are prominent in the neighbourhood of sun-spots.

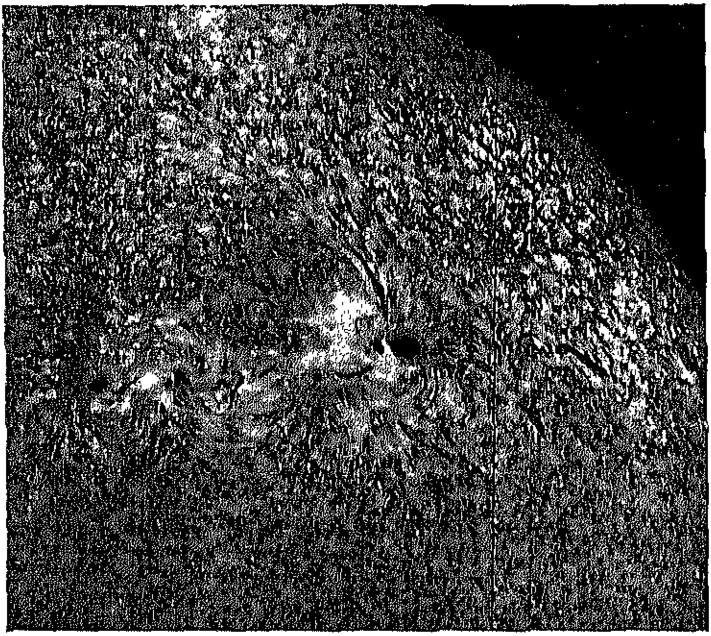
The spectroheliograph is the instrument with which we study solar meteorology—the distribution and movements of certain elements at varying heights in the solar atmosphere. But what has this discriminating instrument to say of the most striking as well as the most enigmatic feature of the sun, namely, the sun-spot? As might be suspected, the apparent darkness of a sun-spot is due to its temperature being lower than that of the brilliant photosphere, and the characteristics of

PLATE VII.

(*a*) (*b*) (*c*)



Three photographs of a Sun-Spot group.
(*a*) direct ; (*b*) in calcium light ; (*c*) in hydrogen light.
*Mt. Wilson Observatory.*



(*d*) Sun-Spot Vortex (hydrogen light).
*Mt. Wilson Observatory.*

the sun-spot spectrum are such as to give a good indication of what that temperature is. The spectrum gives evidence of the existence of compounds such as titanium oxide, which in the laboratory is dissociated into its constituent elements at temperatures exceeding 3000° C. roughly. From considerations such as this, it is concluded that the sun-spot temperature is in the region indicated by the figure quoted. It is well known that if a gas is allowed to expand suddenly there follows a drop in its temperature. Is a sun-spot the visible evidence of some such sudden expansion of the solar gases, and how is this expansion caused? Plate VII (*d*) is a photograph taken with the spectroheliograph in the red light of hydrogen; it is, therefore, a picture of the distribution of hydrogen in the upper strata of the solar atmosphere. The picture is strikingly suggestive of vortex motion—a revolving solar storm, a maelstrom of stupendous magnitude. Is the high-level hydrogen being sucked down into the lower depths, as many a ship has been whirled to its doom in the revolving mysteries of the sea? Hale has actually followed the course of a hydrogen prominence, silhouetted against the luminous gases, in the neighbourhood of a sun-spot until it appeared to be swallowed up as if by a devouring monster. But a discovery, made by Hale, allows further light to be cast into the mysterious depths of sun-spots. The character of a line in a spectrum is altered according to well-known laws—we do not enter into details, otherwise a lengthy digression would be necessary—if the light-producing source is subjected to magnetic influences. When the spectrum lines due to a sun-spot were examined, it was found that such magnetic effects were present. It is now believed that the observed magnetic effects are the result of the vortical or whirling motion of electrons. The existence of vapours of ionised calcium, for example, implies the presence of free electrons in the sun; but the problem still remains unsolved of accounting for the aggregation and characteristic motions of electrons in the spots. Sun-spots generally occur in pairs, but the association is more significant than the mere juxtaposition of two apparently similar objects would indicate. The ends of a horse-shoe magnet are of opposite magnetic kind or polarity, as it is called. So it is with a sun-spot pair. It is as if a gigantic horse-shoe magnet were embedded within

the sun, its ends or poles just protruding through the photosphere. But it may be asked, what, on this explanation, is a single spot without a visible companion? The answer is Hale's discovery of invisible sun-spots, the complements of those spots which on the ordinary photographs appear as isolated individuals. A still more puzzling phenomenon concerns the magnetic characteristics of sun-spot pairs in relation to the sun-spot period. It has been found that these characteristics do not repeat themselves from cycle to cycle. Thus if the leading spot of a pair in the northern hemisphere corresponds to the north pole of a magnet, in the succeeding cycle the leading spot of any pair in the same hemisphere will correspond to the south pole of a magnet; in the next cycle there will be another reversal. Consequently, judged by the magnetic properties of sun-spots the solar cycle is twice the familiar one of eleven years. Despite the great accumulation of facts and the application of new and powerful methods of investigation, the origin of sun-spots and the processes within the sun which find their expression in the sun-spot cycle remain as unsolved problems.

What has the spectroscope to teach us regarding the corona? The spectroheliograph enables the chromosphere to reveal its secrets day by day, but the study of the corona has to be concentrated into the all too brief moments afforded by a total solar eclipse. It is not surprising that progress in coronal investigations is slow. The spectrum of the inner corona (the lowest layers) contains bright lines, sixteen of which have been observed at different eclipses. These lines raise immediately the interesting problem of their origin, for they do not correspond with any lines in the solar spectrum or in laboratory spectra. It is certain that these lines are not the evidence of the existence of a new element which has eluded the vigilance of chemists and physicists, but that the coronal bright lines are due to one or more of the known elements existing under conditions which the physicist has been unable to imitate in the laboratory. Here is a problem which will require the co-operation of the astronomer, the physicist, and the mathematician; the astronomer has to provide accurate information as to the spectrum, the physicist's share concerns the properties of atoms under varying conditions of temperature and pressure,

and the mathematician's the confronting of theory with the facts of observation. The spectrum of the outer corona resembles the ordinary Fraunhoferic spectrum of the sun itself; the inference is that it is due to the reflection or scattering of sunlight by the particles constituting the outer corona, these particles probably being electrons. It is unnecessary to catalogue the various baffling questions which the mere fact of the existence of the corona provokes; in due course its jealously guarded secrets will be successively laid bare under the irresistible attacks of astronomical and physical science.

Let us return to a phenomenon of the chromosphere, which the reader has probably found very puzzling and which has baffled astronomers for a long time. It is the presence of the heavy element calcium in the highest levels of the solar atmosphere and higher still in prominences. The presence of lead pellets floating a mile up in our own terrestrial atmosphere would be a phenomenon at first sight not less startling than the floating vapours of calcium in the chromosphere and prominences. We have seen that the heights attained by the chromospheric gases and vapours can be measured with tolerable accuracy in the flash spectrum, and it is not surprising that the lightest elements, hydrogen and helium, are found high up, the former to a height of about 5000 miles above the photosphere and the latter to a height not very much less. But calcium outdistances both hydrogen and helium. It is evident that calcium possesses some remarkable properties, which recent researches have traced to the peculiar characteristics of the calcium atom itself. The presence of chromospheric calcium is revealed in the spectrum by the prominent H and K lines, and these lines are due, not to the complete atom, but to the singly ionised atom. The first step in the elucidation of the mystery was taken in 1920 by Professor M. N. Saha, who investigated the conditions under which ionisation took place. Ionisation, as the reader will remember, is the forcible removal, from the atom, of an outer electron which consequently becomes an independent entity, pursuing a solitary career—at least for a time. A sufficiently high temperature is one condition for ionisation, for the higher the temperature the greater is the disrupting influence to which the atom is subjected. If the gas pressure is great, that is, if the atoms are tightly packed

together, a discarded electron soon falls in with a damaged atom and completes the atom's complement of planetary electrons. The lower the pressure the less is the chance of the capture of the electron; thus the proportion of ionised atoms in the gas is dependent on the pressure. Moreover, different atoms have different capacities of resistance against the same ionising agency. At a particular level of the solar atmosphere we have certain conditions of temperature and pressure. For one kind of atom these conditions may be powerless to ionise the atom, and the spectrum given by the element will be that of the neutral atom with its complete array of electrons. For another kind of atom the conditions for ionisation may be perfect, and the spectrum will be due entirely to the ionised atoms. For yet another kind of atom the conditions may be suitable for the partial ionisation of the atoms—that is, some will be complete and some ionised—and the spectrum of this particular element will consist really of two spectra, one due to the atom in its ordinary state and the other in its ionised state. In particular, if the proportion of ionised atoms is very small, the lines of the spectrum due to these will be weak as regards intensity, and the lines due to the complete atoms will be strong. When the conditions of temperature and pressure are given, Saha's theory enables the proportion of ionised atoms to be calculated. In particular, if the spectrum shows that at a certain level of the solar atmosphere all the atoms of an element are ionised, the theory gives a definite relation between the pressure and temperature at that level, so that if the temperature is known the pressure can be calculated.

Returning to the consideration of the calcium chromosphere, we note that although Saha's theory can give an account of its constitution in the manner just described, it does not explain its existence. What supports the heavy calcium atoms in the high chromospheric levels and balances the gravitational pull of the sun itself? To answer this question we describe some points in the remarkable investigations of Professor E. A. Milne. It has been known for many years that light exerts a pressure on any surface upon which it falls. With the ordinary sources of light to which we are accustomed the pressure is practically insignificant, and its detection or

measurement in the laboratory is a matter of extreme experimental delicacy. But in the sun and stars light pressure—or, more generally, *radiation pressure*—is a factor of the greatest significance. From the photosphere the sun pours out unceasingly an amazing stream of light and heat, with a great capacity for demonstrating the potentialities of radiation pressure. Let us first of all consider a hydrogen atom exposed to this stream of radiant energy which as the photospheric spectrum teaches us consists of etheric waves with a considerable range of wave-lengths. The hydrogen atom absorbs or swallows discriminatingly a quantum of the incident radiation of a particular wave-length, and in the process is pushed outward from the photosphere. In this state of absorption the planetary electron revolves in an outer orbit and is ready to fall back to an orbit nearer the nucleus; when it does this it emits radiation characteristic of the fall between the two orbits, and is again prepared to undergo the process of absorption. The atom is thus subjected to a series of kicks by the outflowing radiant energy which balance or help to balance the gravitational attraction of the sun's mass on the atom. In this way the atom is supported, as it were, at comparatively high levels above the photosphere. At this point it might be conjectured that this process ought to make possible the support of heavy atoms, such as lead. Of course, the greater the weight of the atom the greater must be the kick imparted by the photospheric radiation, if the atom is not to fall back to the photosphere. The fact that calcium and not lead is found at high levels above the photosphere suggests a fundamental difference in the reaction of their respective atoms to the particular quality of the photospheric radiation. The normal atom of calcium contains twenty planetary electrons. It is believed that their orbits are arranged as follows: two electronic orbits near the nucleus, two groups of eight still further off and, beyond, two outer electrons. Under the conditions prevailing in the chromosphere, one of the outermost electrons is torn off. If the second outer electron is also knocked out of the atom, the remaining eighteen electrons, together with the nucleus, form a very stable structure, upon which the energy pouring out from the photosphere would have little or no effect; that is to say, that the calcium atom with but eighteen

electrons left would receive kicks of such feebleness that support above the photosphere would be impossible. The phenomenon of the calcium chromosphere must then be due to the peculiarities of the remaining outer electron of the calcium atom, or rather of the various orbits in which it can revolve. As regards many other elements, excluding hydrogen and helium, the absorption of the photospheric radiation removes the outermost electrons to such distant orbits that the atoms are effectively shorn of their outer screen of electrons, and are therefore reduced to the stable structure upon which the outpouring solar energy has no effect; they therefore fail to rise above the photosphere. But with the singly-ionised calcium atom the circumstances are different. The wave-lengths of the solar radiation are such that the atom can absorb energy (of the requisite wave-length) very much less in amount than would be necessary to drive the electron out of the atom altogether. In other words, the outer electron can function—under the influence of the photospheric radiation—in orbits not very remote from its normal orbit. And, moreover, the quantum of energy absorbed by the atom is of such magnitude that the kicks imparted to the atom are sufficiently great to neutralise—with something to spare—the gravitational pull by the solar mass. The atom is consequently driven outwards from the photosphere until equilibrium between the two antagonistic forces is reached. Such, in brief outline, are the physical processes by which Professor Milne explains the remarkable characteristics of the calcium chromosphere. It may be added that the tenuity of this calcium envelope is as remarkable as the great height to which it attains above the sun's photosphere, for the amount of chromospheric calcium is extremely minute in relation to the vast space which it occupies. Its weight is estimated at 300 million tons—a minor planet, a quarter of a mile in diameter, with a composition similar to that of the earth, would be as massive as this tenuous but extensive envelope which we know as the calcium chromosphere.

Now the process undergone by the ionised atom consists of two parts: the first is absorption, at the end of which the outer electron has jumped from its normal orbit to a more distant one; the second is emission of radiation, at the end of which

the electron has returned to its normal orbit after emitting the characteristic light of wave-length corresponding to the loss of energy suffered in its drop between the two orbits. From the information supplied by the spectral lines (the H and K lines) and the mathematical application of these principles of absorption and emission, Professor Milne has succeeded in evaluating (incredible as it may appear) the average periods in which the outer electron of the chromospheric calcium atom remains in its normal orbit and in its upper or outer orbit. The first period is about one twenty-thousandth part of a second, the second period is about one fifty-millionth part of a second. The first period depends on the intensity of the photospheric radiation, for the more intense the stream of outflowing radiation the less is the time during which the atom requires to wait before picking up another packet of energy. But the second period is not dependent on the atom's environment; it is, in fact, a characteristic of the atom itself. It is a strange peculiarity of the theory of light quanta that the atom appears to be endowed with the power to pick and choose. For example, if an electron can jump under the influence of radiation from its normal orbit to one and only one other, the atom ignores all the incident radiation except that of one particular wave-length, and the result is absorption. After a definite but brief interval, the electron decides (as it were) to return to its normal orbit; light is emitted and the atom is again ready for another cycle of absorption and emission.

Such—in some of its simplest aspects—is the theory of the calcium chromosphere. A theory must be submitted to tests, and the remarkable theory just described can be associated with certain predictible effects in the chromospheric spectrum. We do not go into details, but it may be added that one test made by Col. F. J. M. Stratton and Mr. C. R. Davidson at the Sumatra eclipse of 1926 afforded satisfactory confirmation. A more exhaustive test was planned by several eclipse parties in England and Norway at the 1927 eclipse, but bad weather conditions prevented the carrying out of the observations. Since then, Mr. Davidson has succeeded in making spectroscopic observations of the sun at Greenwich, with results in good agreement with Professor Milne's theory.

In the previous pages we have had frequently to refer in a general way to the sun's radiation of light and heat, and to the temperature at or above the photospheric layers. The rate at which the sun pours forth its radiant energy is measured by the heating effect produced by the sun's beams on an instrument called the pyrheliometer. But the sun's rays have to traverse our own enveloping atmosphere, thereby suffering absorption, which has to be allowed for in estimating what would be the heating effect produced if the earth's atmosphere were non-existent. Moreover, this absorption is not the same for all wave-lengths, and the problem of determining the magnitude of the absorbing effect of our atmosphere is therefore one of no little complexity and difficulty. When this estimated correction is applied, the solar constant of radiation, as it is called, is obtained. Without introducing refinements into our definition, the solar constant is the measure of the amount of radiant solar energy which, limited to a beam or cross-section of one square centimetre, would in one minute raise the temperature of one gram of water by 1°·94 Centigrade on the earth—the earth being at its mean distance from the sun and atmospheric absorption being supposed non-effective. From the data it is easy to calculate the rate at which energy pours outwards across one square inch of the solar photosphere —it is equal to the rate of work done by a perfect engine of about 50 horse-power. If the sun were a perfect radiator of heat and light energy, physical laws and the value of the solar constant would combine to give the *effective temperature* of the sun—or rather of the photosphere; the result is about 6000° C. Below the photosphere the heat of the solar furnace grows fiercer and fiercer; the atoms of the elements—as we know them on the earth—are shorn of their encircling electrons and matter is reduced, within the most secret recesses of the sun, to a confused medley of atomic nuclei and electrons. This may seem a fanciful picture, but we are merely anticipating conclusions which will be more fully described in a later chapter. But meanwhile the reader will naturally ask: "What is the source of this stupendous output of energy, and how long can it last?" A cognate question immediately suggests itself: "Are the stars, in their myriads, pouring forth radiant energy into the waste places of the universe with similar prodigality,

and what are these mysterious reservoirs of energy which since the first appearance of man upon the earth till these days in which we live show no sign of exhaustion?" Again we ask the reader's patience; when we have made a survey of our marvellous universe, then is the time to try to peer into the mysterious places where—it would seem—Nature has made herself invisible.

# CHAPTER VII

## THE MOON, THE PLANETS AND COMETS

THE moon is our nearest celestial neighbour ; compared with the great planets, the glorious sun itself and the myriads of stars that sparkle in the firmament, it is a body of insignificant proportions, a tiny speck in the vast universe revealed by modern researches. But owing to its nearness the moon assumes an importance to mankind second only to the sun. The moon is the earth's satellite revolving in an orbit around the earth

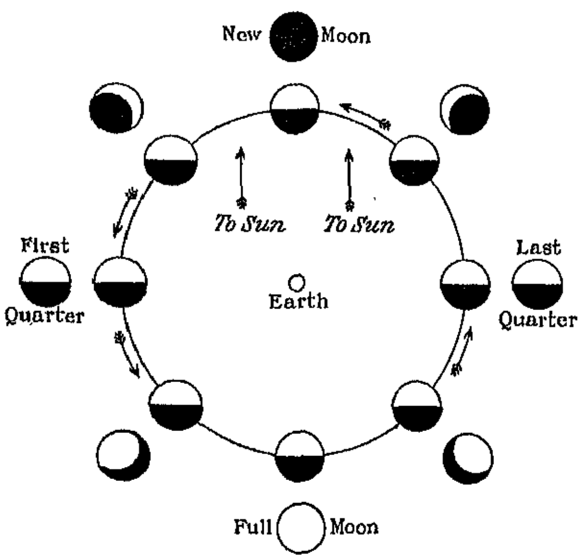



FIG. 52.—THE PHASES OF THE MOON.

at an average distance of about 240,000 miles in a period of $27\frac{1}{3}$ days. Its diameter is 2163 miles, its mass is about 1/81 of the earth's mass, and its density is 3·4 times that of water. The moon revolves about an axis in a period equal to that of its revolution around the earth. The consequence is that the

moon presents the same hemisphere towards the earth. Certain circumstances, however, mainly connected with conditions pertaining to the moon's orbit, conspire to increase the surface area that can be seen from time to time to about three-fifths of the total lunar surface, the remaining two-fifths remaining for ever a mystery to terrestrial observers.

The beautiful succession of changes which the visible surface of the moon undergoes from day to day—the moon's phases—is due to the continuous alteration of the moon's position with regard to the positions of the sun and earth. This is illustrated very simply in Figure 52 (not drawn to scale). The moon is a dark body, only made visible by the reflection of sunlight from its surface. The diagram shows the moon at various points of its orbit around the earth, and the hemisphere towards the sun is shown illuminated. The appearance of the moon as seen from the earth is illustrated at intervals between full moon and new moon. The interval between new moon and the next new moon is called the lunar month, and is on the average $29\frac{1}{2}$ days—it is the average interval between successive conjunctions of the sun and moon.

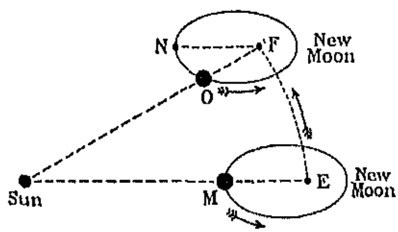


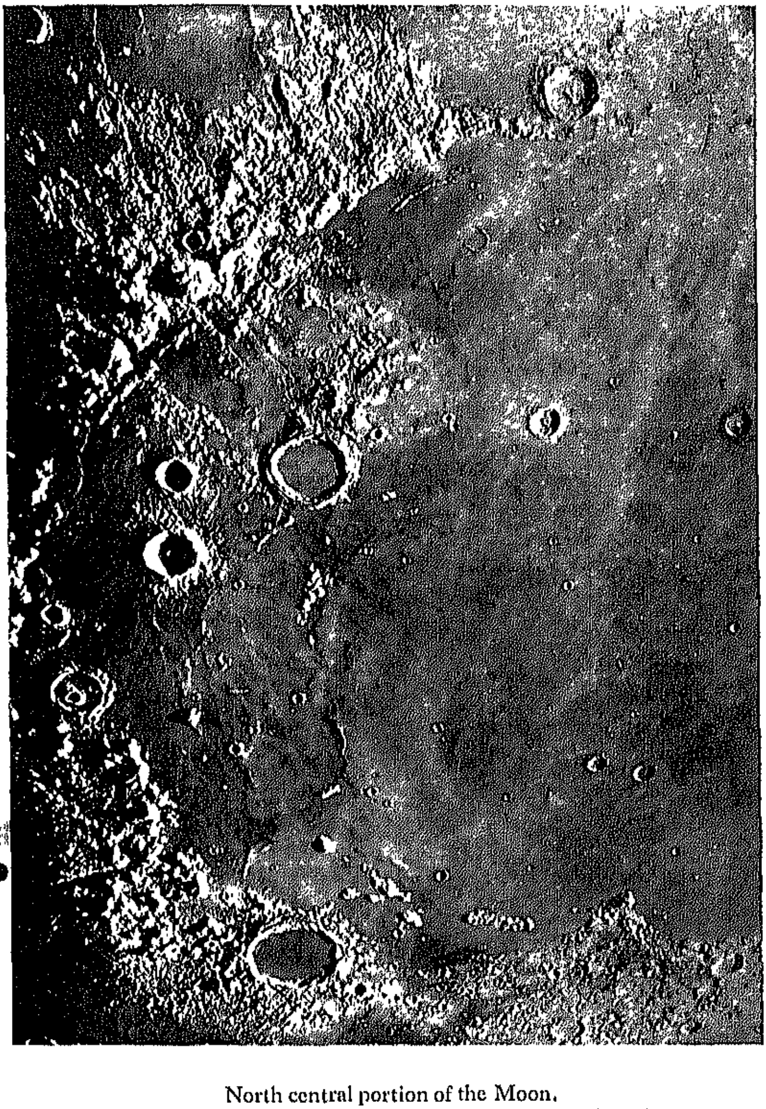

FIG. 53.

This is longer than the moon's orbital period, to which we have previously alluded; the relation of the two may be understood from Figure 53, which shows the orbit of the earth about the sun, and the orbit of the moon about the earth at the beginning and end of a period of $27\frac{1}{3}$ days—starting at a new moon. At the end of this period the moon is represented at N, having made one complete revolution in its orbit. But it is not new moon yet at N—the moon will have to revolve in its orbit towards O, when the moon will be again in conjunction with the sun. Thus the interval between new moon and new moon is longer than the time required for a complete orbital revolution.

In the lives of men the moon plays two important rôles: for part of the lunar month it is a luminary at night, and its attraction on the waters of the earth is the main cause of the

tides, of which every port on the earth takes full advantage. We do not stop to amplify these statements, but pass on to describe the appearance of the moon as seen in the telescope.

The smallest telescope will reveal the chief topographical features of the lunar surfaces—the rugged mountain ranges and a vast number of craters and walled-in plains, some with central peaks towering high above the lunar landscape. With large telescopes other features catch the eye : the black shadows cast by the mountains and the crater walls (the measurement of the lengths of the shadows enables the height of these to be deduced), the streaks that radiate in all directions without regard to the lunar contours from one or two of the largest craters, the rills—sometimes several hundred miles in length—which appear to be great furrows on the moon's surface, the vast plains of varying shade dotted here and there by small craters and, most remarkable of all, craters situated within craters. The photograph (Plate VIII) shows better than words can describe the ruggedness, the appalling desolation, of the moon's surface. The moon is, in fact, a dead world, airless, changeless and lifeless. Perhaps this description may be regarded as an overbold generalisation, a too dogmatic assertion, but in its general terms it is undoubtedly true. At times, minute changes have been suspected. In the earlier maps of the lunar topography a small crater—called Linné—5 or 6 miles in diameter, was shown as a definite feature. In 1866 Schmidt, of Athens, announced that it had disappeared ; its place is now occupied by a small dark spot. If the earlier maps are to be trusted—and there is little ground for suspecting their accuracy—the disappearance of Linné may be explained quite naturally as the result of the falling-in of the crater walls. Again, Professor W. H. Pickering, who has spent a lifetime observing the surface features of the moon and planets offers his testimony of exceedingly minute changes in several regions, notably on the floor of the large crater Eratosthenes, which he attributes to the seasonal cycle of a low form of vegetation, grey in colour. He also asserts that he has seen traces of clouds and snow patches, pointing to the existence of a very rarefied atmosphere. It is not impossible that Pickering's observations have a solid foundation of reality behind them despite the present general belief that the moon is a dead world.



North central portion of the Moon.
The large crater near the centre of the photograph is Archimedes, with a diameter of about 50 miles)
*Mt. Wilson Observatory.*

What is the origin of the crater formations? Two explanations have been proposed, but neither is satisfactory. There is first the explanation which presupposes volcanic action in past ages on a grand scale. The largest crater, it may be mentioned, has a diameter of 150 miles and an area half as large again as that of Ireland, and there is a considerable number with diameters of 50 miles and over. The main objections to this hypothesis refer to the colossal scale of lunar eruptions necessary for the formation of the giant craters, and to the absence of lava flows. The second explanation of the formation of craters carries us back to the time when the moon was still plastic, with its crust not far from the point of solidification; the craters, on this hypothesis, are the visible and enduring evidence of a bombardment by meteors, great and small. The earth is continually being bombarded by meteors which, vaporised by the frictional resistence of our atmosphere, generally perish in a streak of glory. A few occasionally succeed in penetrating our atmospheric shell—sometimes they weigh several tons—and finish up their wandering cosmic life in the unexciting seclusion of a great museum. There is, therefore, no doubt about the meteoric bombardment of the earth, and there can be none as regards the moon, either in the present or in the past. The main objection advanced against this hypothesis is based on the inference that such impacts must all be vertical, or nearly so, to account for the almost perfectly circular forms of the craters, whereas there is no *a priori* reason why meteors should fall vertically and in no other direction. But this objection becomes invalid if the crater is supposed to be the result of a meteor imbedding itself in the almost solid lunar crust, the friction, as before, vaporising at least the outer parts of the meteor, upon which follows a shattering explosion. The effect of high explosives during the Great War lends some colour to this theory. The meteors, of course, must have been enormous in comparison with those of which we have experience now—in fact, they must have been comparable in size with the minor planets—if they are to be held responsible for the origin of the great lunar craters.

Mercury, the planet nearest the sun, is a small body with a diameter of about 3000 miles—40 per cent. greater than

that of the moon. It has no satellite, and its mass cannot, in consequence, be determined according to the usual method. Its gravitational effect on the orbit of a neighbouring planet, however, depends on its mass, and if the magnitude of the perturbations can be determined, the mass of the planet can be deduced. In this way the mass of Mercury is found to be about one-twentieth of the earth's mass. Owing to its proximity to the sun, Mercury is a difficult object to observe; at the most, it can be but 28° from the sun. In the telescope, Mercury is seen as a crescent, thin when near the sun, and like a half-moon when at its greatest angular distance from the sun. Its surface shows none of the distinctive marks so characteristic of the moon's surface. Its rotation period is not known for certain. Like the moon, Mercury appears to be devoid of an atmosphere.

The most notable feature of Mercury is the high eccentricity of its orbit around the sun; at perihelion (the point of the orbit nearest the sun), the distance between Mercury and the sun is 0·31 astronomical units, or about 29 million miles, and at aphelion (the point of the orbit most distant from the sun), the distance is 0·47 astronomical units, or about 43 million miles. We have seen in a previous chapter that the effect of the attractions of the planets on an orbit such as Mercury's can be calculated by the application of Newton's law of gravitation. By the middle of last century it became clear that Newton's law was insufficient to account for the observed motions of Mercury; there was, in fact, a remarkable discrepancy between gravitational theory and observation. Because of the high eccentricity of the orbit the direction of Mercury when in perihelion as seen from the sun can be determined with great accuracy with reference to the background of the stars. Observation showed that after the disturbing effects of all the known planets had been taken fully into consideration, there was a gradual change in the direction of the perihelion position of the planet. This may be made clearer by reference to Figure 54, in which we shall suppose the full line curve to represent the orbit of Mercury in 1800; P is the point of the orbit nearest the sun, and the direction of SP with reference to the stars is accurately known. The changes in the orbit between 1800 and 1900, due to the attraction of the known planets, can be

calculated, as we have said, from the Newtonian law. If these alterations are removed from the orbit observed in 1900, we should evidently arrive back at the 1800 orbit; that is to say, the full line curve in Figure 54, on the assumption, of course, that our catalogue of planets is complete and that the Newtonian law is an accurate astronomical law. But we do not arrive back at the 1800 orbit; instead, we find that the orbit has been rotated, as it were, in the interval so that the direction of the nearest point Q of the orbit has moved through an angle QSP, which is found from observation to be 42 seconds of arc. This may appear to be a small change in direction in 100 years. In one year the change is just the angle subtended by the diameter of a halfpenny placed 8 miles away. But science cannot afford to ignore any discrepancy, however minute, between current theory and facts of observation. In astronomy such discrepancies have led to the most notable discoveries — we may recall the remarkable feat of Adams and Le Verrier in predicting, from the observed irregularities in the motion of Uranus, the existence of the then unknown planet Neptune. In the present instance there were two lines of approach to the elucidation of the anomaly presented by Mercury's orbit: firstly, the possibility of the existence of one or more small planets within the orbit of Mercury; and secondly, the possibility that Newton's law was not a completely accurate representation of the natural law governing the movements of the sun's family of planets. We have referred to the difficulty of observing Mercury itself; an intra-Mercurial planet (that is, one nearer the sun than Mercury) would be a still more difficult object to observe, and the best chance of its discovery would occur during a total eclipse of the sun. On the assumption that the observed discrepancy in the orbit of Mercury is due to the attraction of a hypothetical intra-Mercurial planet, the mass of the unknown can be calculated; it is found that this

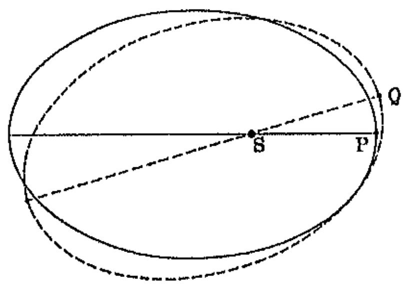


FIG. 54.

mass must be at least one-seventh of the mass of Mercury, and therefore that the unknown must be a considerable planet with a diameter at least half of Mercury's. Searches have been made at recent eclipses without any success, and the conclusion is unmistakable that the mysterious behaviour of Mercury cannot be attributed to this or a similar hypothesis.

In 1916, Professor Albert Einstein revolutionised the fundamental concepts of space and time in his celebrated theory of generalised relativity. Our experience seems to indicate that space—length, breadth, and depth—and time are independent entities, but the theory of relativity shows that they are particular aspects, which are analysed by ourselves, of a four-dimensional space-time world, just as length, breadth, and depth are particular aspects of the analysis of what we ordinarily call space. In the neighbourhood of matter the space-time world has certain definite properties, and in the neighbourhood of the sun, in particular, their effects are

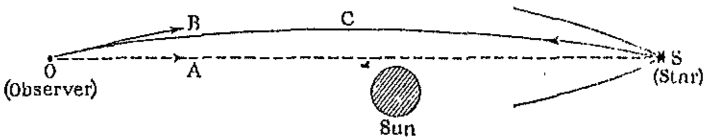



FIG. 55.

slightly different from the effects implied in Newton's law of gravitation. The theory of relativity can predict the motion of Mercury around the sun, and the discordance which we illustrated in Figure 54 is exactly accounted for by the theory. It is impossible to describe in a few lines the revolutionary character of Einstein's theory; here we emphasise the astronomical phenomena by which it can be tested. The circumstances of Mercury's orbit furnish one test from which the theory emerges triumphant, and we now interpolate a brief description of the second and third astronomical tests. A ray of light from a star traverses space in a straight line; if, however, for example, the ray passes close to the sun, its path is governed by the laws of relativity space around the sun, and the ray is no longer straight, but curved. For the sun, this effect can be calculated; if the ray just grazes the sun's disc, it is "bent" or deflected by the minute amount of $1\frac{3}{4}$ seconds of arc, and the effect falls off for rays which pass at

increasing distances from the sun. In Figure 55 are traced the rays from the star S. For example, if the sun had no influence on the starlight the direction in which an observer O on the earth would see the star is along OA, the straight line joining O and S. Actually, the star is seen in the direction OB, the curve SCO representing the curved ray which reaches the observer from the star. The difference between the directions OA and OB is due to the sun. The effect, then, is that the star is seen further away from the sun's disc than would be the case if the sun's influence were non-existent. The detection of the predicted deflection constitutes the second test of the theory of relativity. The circumstances of a total eclipse of the sun evidently supply the necessary condition for the successful photography of stars near the sun. Such a photograph must then be compared with another in which the star images are due to rays uninfluenced by the sun (this latter photograph can be made—with the same telescope—a month or two after the eclipse under ordinary night conditions). Let us suppose that the two plates are superimposed, one on top of the other. If there is no displacement of the images in the eclipse plate of the kind contemplated, it would be possible to fit one set of images over the other. If the relativity effect operates, a fit is impossible and the star images on the eclipse plate appear a little further away from the centre of the eclipsed sun than the corresponding images on the other plate. This is illustrated diagrammatically in Figure 56, in which the open circles represent the star images on the eclipse plate and the dots the images of the corresponding stars on the other plate; needless to say, the displacements in Figure 56 are very much exaggerated. The displacements can be measured, and if the measures conform to the prediction of the relativity theory, the latter has again been vindicated. Such tests were first made at the 1919 eclipse, and the results were such as to afford confirmation of the theory; later eclipses furnished further evidence of the genuineness of the effect predicted by relativity.

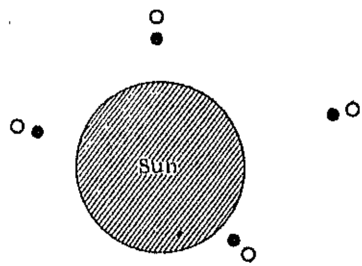


FIG. 56.

The third test is a much more difficult one to carry out. It depends on the relation between the behaviour of atoms in the sun and that of similar atoms on the earth. The influence of the sun's mass, say on an atom of iron in the solar atmosphere, is such as to increase slightly the wave-length of any particular iron line in the solar spectrum as compared with the wave-length of this line produced in the laboratory. The difference predicted by the theory is small, although within the powers of detection of modern apparatus. We need not consider the various difficulties encountered in making the test, but it is now certain that the theory of relativity has scored yet a third success. We shall see later the remarkable application of this third test in another sphere.

We now pass on to consider the physical characteristics of the next planet, namely, Venus. As regards dimensions and mass, Venus, of all the planets, most closely resembles the earth; its diameter is about 7600 miles, and its mass is about four-fifths of that of the earth. Venus, like Mercury, has no satellite, and its mass is measured by means of the observed disturbing effects on the orbits of the neighbouring planets. Venus possesses a dense cloudy atmosphere which effectively conceals its surface features. Consequently, in the absence of any but very indefinite markings, the measurement of the planet's period of rotation by visual observations is extremely difficult. Several observers have asserted that the period is 225 days—the same as its period of orbital revolution around the sun. If this were so, Venus would always have the same hemisphere turned towards the sun, just as the moon presents the same hemisphere towards the earth; the consequences would be remarkable, for the hemisphere towards the sun would enjoy perpetual day, the other hemisphere would be doomed to perpetual night. Recent observations, however, appear to be fairly conclusive against this view. With a delicate instrument, called the thermopile, the heat radiation of a faint source can be measured. If one hemisphere of Venus were perpetually unillumined by the sun's rays it could radiate very little heat. Thermopile observations definitely record an appreciable amount of heat radiated from the dark hemisphere, and this fact seems to rule out a rotational period of 225 days. We have seen, in the case of the sun, the application

of Doppler's Principle to the measurement of the solar rotation. At the Lowell and Mount Wilson Observatories a similar series of observations has been undertaken with respect to Venus; a rotational period of at least five days is indicated.

What is the constitution of the planet's atmosphere? Does it contain oxygen and water vapour, which are of such importance to terrestrial life? We evidently submit these questions to the judgment of the spectroscope. The light which reaches us from Venus is sunlight which has penetrated the atmosphere of the planet to a certain depth, where it suffers reflection and scattering; the reflected light makes a return passage through the intervening layers of atmosphere, and then traversing our own terrestrial atmosphere enters the slit of the spectroscope. During its double passage through the planet's atmosphere and its passage through the terrestrial atmosphere the sunlight suffers absorption by the gaseous elements and compounds in its path, and in consequence of the principles of spectrum analysis the spectrum of Venus ought to show absorption lines or bands characteristic of these substances. The absorption lines and bands due to terrestrial oxygen, etc., can be studied in the ordinary solar spectrum, and so their effects can be taken into consideration in the spectrum of Venus. The results of recent spectroscopic investigations seem to indicate conclusively that, in the atmospheric layers of Venus through which the sunlight passes, oxygen and water-vapour are absent. But this does not mean that the planet's atmosphere is destitute of these substances. If the solar light is reflected by clouds at high atmospheric levels, the observations are, in a sense, evidence of our failure to penetrate to more interesting depths. Beyond the fact of its existence, the atmosphere of Venus remains an enigma.

The question of the possibility of life on neighbouring planets or in more distant regions of the universe is one that appeals instinctively to the imagination. The question has been raised as regards Mars, and we shall see in later pages the kind of answer which modern astronomy is prepared to give. Is Venus a possible abode of life? Here we enter the region of speculation, for our knowledge of the planet, as we have seen, is extremely limited. The justification of speculation consists, firstly, in the general resemblance of Venus, as regards

size and mass, to our own earth, suggesting a parallel course of evolution from the remotest times; and, secondly, in the existence of an atmosphere of whose constitution, however, we are wholly ignorant. Perhaps we are entitled to say that the physical conditions on the surface of Venus are probably similar to those on the earth, and to add that whatever professions may flourish on Venus that of the astronomer will almost certainly be unknown.

Of all the planets that have excited the curiosity and speculation of astronomers and laymen alike, Mars, by reason of the phenomena associated with its surface markings, stands out foremost. With the exception of Venus, Mars at the most favourable oppositions approaches more closely to the earth than any other major planet. The orbit of Mars has a comparatively high eccentricity, so that its distance from the earth at an opposition varies between 35 and 63 million miles. The last favourable opposition was in August, 1924, when Mars was very near its minimum distance from the earth and, as we shall see, the opportunity to make an intensive study of the planet was eagerly seized by astronomers.

The diameter of Mars is 4200 miles, which is approximately half-way between the diameter of the moon (essentially, if not entirely, a dead world) and the diameter of the earth, the abode of many forms of life. Mars rotates about an axis in 24 hours 37 minutes; thus the Martian day is almost the same as the terrestrial day. The period of orbital revolution is 687 days; the Martian year is thus a little less than two terrestrial years. The inclination of the planet's equator to the plane of its orbit is nearly 25°, so that the Martian seasons bear a strong resemblance to our own seasons. Owing to its greater distance from the sun, Mars receives roughly about one-half of the heat and light which we receive from the sun. Judged from these circumstances alone, the similarity between Mars and the earth is very striking.

Mars has two satellites, discovered by Professor Asaph Hall in 1877, named Phobos and Deimos. These are minute bodies between 10 and 50 miles in diameter. The former makes a complete revolution in its orbit around Mars in 7 hours 39 minutes, the latter in 30 hours 18 minutes, in the same direction as that of the planet's rotation. The circumstances

attending the revolutionary period of Phobos are remarkable, indeed unparalleled in the solar system, for it revolves roughly three times faster than the planet rotates, and the consequence is that to a hypothetical Martian observer the satellite rises in the west and sets in the east. Deimos behaves in the more prosaic way of rising in the east and setting in the west. Phobos is but 3700 miles from the planet's surface, and as its orbital plane coincides with the planet's equatorial plane, it cannot be seen in Martian latitudes higher than about 69° ; and neither satellite is visible from the poles. It is very rare that writers of fiction soar into flights of astronomical fancy which in later generations are found to have a solid substratum of fact, and so it is rather a curious coincidence that in *Gulliver's Travels* the astronomers of Laputa, equipped with good telescopes and keen vision, should "discover" two Martian satellites, one revolving in the remarkable period of 10 hours and the other in 21½ hours.

In discussing the physical features of Mars—its surface markings, atmosphere and the like—it is well to remember that until recently observations of the planet were entirely visual, and therefore that the perception of fine detail on the planet's surface depended principally on an efficient telescopic equipment, on the observer's keenness of vision and on the steadiness and transparency of our own atmosphere above the observer's station. This last condition—that of good "seeing," as it is called—is not so easily and continuously experienced as might seem likely. It is not surprising that controversies have raged over the authenticity of features alleged to have been seen by some observers and denied by others. In a discussion on Mars an historical treatment appears, to the writer, to be advisable with emphasis on the salient features corroborated by observations other than visual.

Less than thirty years after the invention of the telescope, vague markings on the planet's disc were first observed, and in 1659 the first drawing of the surface features was made by the Dutch astronomer, Huygens, who also deduced the rotational period to be about 24 hours. In 1719, Miraldi discovered two brilliant white spots which are now known as the Polar Caps. Sir William Herschel observed Mars assiduously at favourable opportunities between 1777 and 1784 ; at first he

was inclined to believe that the Polar Caps were fixed features of the Martian surface, but later observation showed him that the spots varied in size according to the season on Mars. On the earth we have two Polar Caps—the Arctic icefield and the Antarctic snow-covered continent; in our northern summer the snow and ice limit is pushed further and further back towards the North Pole, and simultaneously the Antarctic cap grows in extent during the southern winter. To Herschel the similarity in behaviour between the Martian Polar Caps and the terrestrial snow and ice caps was significant, and he concluded "that the bright polar spots are owing to the vivid reflection of light from frozen regions, and that the reduction of the spots is to be ascribed to their being exposed to the sun." Herschel further obtained some evidence that Mars possessed an atmosphere, from which he was led to surmise "that the inhabitants of Mars probably enjoy a situation in some respects similar to our own."

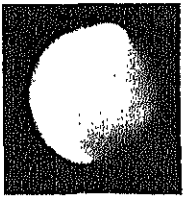
To the observer of Mars the feature that strikes him first is the contrast between the different areas of the surface, for great tracts are reddish and other great areas are bluish-green. In the charts of the middle of the nineteenth century these areas are described respectively as "continents" and "oceans" after the terrestrial analogy. But "ocean" is a misnomer, for if the dark areas were really seas in our sense of the word they would act as great mirrors, in which the terrestrial observer would perceive the brilliant reflection of the sun itself. For this reason alone the nomenclature is unfortunate; however, the names still persist, and therefore we must remember that a Martian ocean is not a watery expanse.

In 1877, the Italian astronomer, Schiaparelli, announced his discovery of the "Canali"—narrow, faint lines intersecting the Martian continents. This word was unfortunately translated into English as "canals," which immediately suggested an intelligent and purposeful agency. Two years later, Schiaparelli made a further announcement that seemed at first as dubious as it was astonishing, namely, that one of the canals had now become double, like the two parallel rails of a tramway line. Later visual observers have reported a similar doubling of canals. In 1892, Professor Pickering made a further addition to Martian geography—minute dark areas occurring almost

invariably at the crossing place of one canal with another; these were first designated "lakes," and later "oases." But it soon became evident that the division of the Martian surface into continents and oceans was entirely erroneous. In the first place, the colour of the so-called seas underwent a seasonal cycle, suggesting the vernal growth and subsequent autumnal decay of vegetation; and in the second place, Pickering, in 1892, observed several canals crossing the dark areas, thus ruling out effectively the notion that the latter were really seas. In 1894, Professor Percival Lowell built and equipped a new observatory at Flagstaff, Arizona, 7000 feet above the sea-level, with the principal object of studying the physical characteristics of the planets generally and particularly of Mars. The site was chosen with great care, so as to secure the best possible conditions of seeing. Lowell soon became the chief exponent of the theory regarding the habitability of Mars. The existence of an atmosphere was established as a result of occasional observations of clouds floating high above the surface. The melting polar cap was observed to be bordered by a bluish ring contrasting with the white area as spring and summer on Mars advanced, suggesting the formation of a temporary sea or marsh by the melting ice or snow. All these observations and others which we need not specify appeared to leave no doubt that Mars possessed an atmosphere, thin compared with our own, a certain amount of water as evidenced by the polar caps, and a vegetation of some sort that passed through a seasonal cycle. In addition, there was the system of canals. (Plate IX (6) shows a reproduction of a recent drawing.) To Lowell the canals were artificial, the manifestation of human effort to maintain a precarious existence in the face of great natural odds, for he supposed them to be the means whereby the not too plentiful water, mainly concentrated at the poles, was conducted to more equable regions. Lowell's conclusions were assailed on all sides, mainly on the ground that the canals were really non-existent, in fact a kind of optical illusion, although the scientific honesty of Lowell and other astronomers who had observed the canals was never called in question. Could photography lend its aid to furnish independent evidence as to the physical characteristics of Mars? A parallel test could be made between the visual and

photographic records of Jupiter, a much easier object to photograph than Mars; if the photographs could show sufficiently delicate detail so as to corroborate the visual observations of that planet, the photographic study of Mars might then be expected to rest on a sure foundation. At a close opposition the angular diameter of Mars can be as large as 23 seconds of arc, less than one-eightieth of the angular diameter of the moon. On a photographic plate the image of the planet is but a fraction of an inch in diameter; it is therefore clear that delineation of fine detail in an image so small must depend on a very efficient technique and on the best possible observing conditions. At the Lowell Observatory thousands of photographs of Mars, Jupiter, and other planets have been taken, and those of Jupiter, for example, have confirmed the visual observations made on that planet. What about the photographs of Mars? The successors of Lowell at Flagstaff affirm that the photographs corroborate the visual observations of Mars in every detail; in particular many of the canals observed visually have been recorded photographically. In this connection, it may be added that the photographs of Mars taken at Lick Observatory during the 1924 and 1926 oppositions add general corroboration to the conclusions reached at Flagstaff (see Plate IX, 5 and 6).

We now describe the new line of attack at the 1924 opposition. Mr. W. H. Wright, of the Lick Observatory, adopted the expedient of photographing the planet through three coloured glass screens, to which we shall refer as the red, yellow, and violet screens. Let us first consider the yellow screen. It is placed immediately in front of the photographic plate, so that the light from the planet has to pass through the screen before recording its message on the plate. Now a yellow glass screen allows only the yellow light to pass through; moreover, yellow is the colour to which the eye is most sensitive, and consequently the "yellow image" ought to be a faithful reproduction of the visual appearance of the planet, revealing the observed contrasts of its surface markings. Photographs of the Martian disc taken through the red, the yellow, and the violet screens we shall refer to simply as the red, the yellow, and the violet images respectively. A long series of observations showed unmistakable differences in the red, yellow, and violet images.



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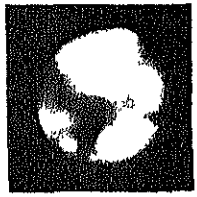


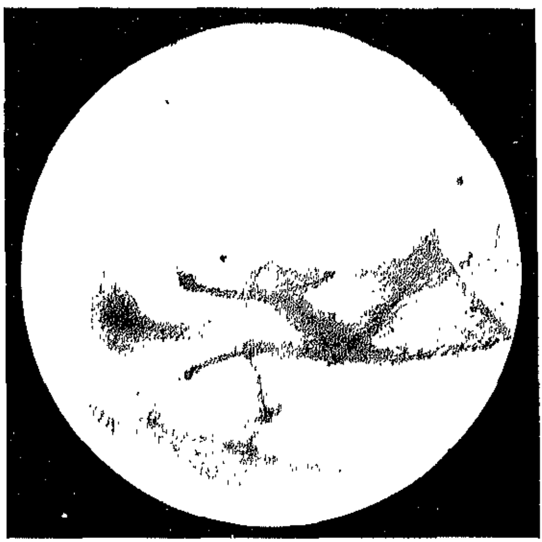
2

3

4

Photograph of Mars in violet light (1), in infra-red light (2),
Photograph of San José in violet light (3), in infra-red light (4).
*Lick Observatory.*

5



6

Infra-red photograph (5) and drawing (6) of Mars, made on the same night.
*Lick Observatory.*

The red images show high contrast in what are believed to be the permanent surface markings; in the yellow images the contrast is somewhat less pronounced, and in the violet images there is unrelieved monotony (except for the polar caps) with not the least suggestion of markings, such as the red and yellow images exhibit. (See Plate IX, 1 and 2.) The interpretation of the remarkable differences between the red and violet images (we need not consider the yellow images in this connection, as they are intermediate in character between the red and violet) is found in the existence of a Martian atmosphere and in its behaviour to the incident sunlight. We must remember that we see Mars by means of the light from the sun reflected by it, and that sunlight, or rather the total solar radiation, consists of light or radiation of different wave-lengths. If we consider for a moment the effect of our own atmosphere with respect to light of different wave-lengths, we shall be in a better position to appreciate the explanation of the differences in the red and violet images of Mars. On a cloudless day the sky is blue. Why? The reason lies in the greater scattering effect, produced by the gaseous and other particles in our atmosphere, on the shorter wave-length components of sunlight—that is to say, the blue components. The result is that the eye receives from all directions (other than that in the direct line of the sun) a preponderance of blue light which, as it were, has succeeded in zig-zagging through the atmosphere. Consequently, if we look at the sky in a definite direction we receive the aggregate of all the blue light which has tortuously found its way through the atmosphere, and which finally reaches our eye in that particular direction. Light of much greater wave-length, in particular red light, is scattered hardly at all. To this fact is ascribed the red appearance of the setting sun, for now the thickness of the atmosphere through which the light has to pass is much greater; consequently, most of the light of shorter wave-lengths is scattered without ever reaching the eye (the effect is intensified if we are looking at the sun through a slight haze or dust cloud), and only the red components of the sunlight succeed in penetrating to the eye. Consider now the sunlight which falls on Mars. The short-wave radiation is scattered by the upper strata of the Martian atmosphere; the long-wave radiation penetrates to the surface

and, reflected there, traverses the atmosphere outwards a finally reaches our telescopes. A further example of simi phenomena is illustrated in Plate IX, 3 and 4, which shows t photographs of San José, taken from Mt. Hamilton, one throu a violet screen, the other through a red screen. In the vio photograph all details are obliterated owing to the scatteri of the violet light in its passage through the atmosphe between San José and Mt. Hamilton, whereas in the red phot graph the details are beautifully depicted. If we cut out but the violet light, as we do when we photograph the plan through a violet screen (the wave-length of violet light is short than that of blue light), the image on the plate is essential the photograph of the upper strata of the Martian atmospher whereas when we cut out all but the red light, the red ima is a photograph of the Martian surface. Such is the explan tion of the differences between the red and violet images.

If the Martian atmosphere is at all extensive there shou be a marked difference between the sizes of the red and viol images, for the radius of the latter ought to be the radius the red image, plus the height of the atmosphere. Mr. Wrigl found that the violet images were definitely larger than th red images, and from the measures he concluded that th Martian atmosphere is about 60 miles high. The visu observers, as we have seen, established the existence of a atmosphere; the 1924 (and the 1926) photographic observa tions have confirmed it in a novel way, and in addition the have provided a reliable estimate of the height to which th atmosphere extends. This height is about half of the heigh of the earth's atmosphere (deduced from observations o meteors, to which reference will be made later), but this approxi mate ratio in height does not mean a similar ratio i atmospheric density. The surface density of an atmospheri envelope depends (amongst other things) on the gravitationa attraction of the planet on the particles constituting th atmosphere; at the surface of Mars this is much less than at the surface of the earth. When these considerations are taken into account, it has been estimated that the density of the atmosphere at the surface of Mars is about half the density of our own atmosphere at the summit of Mt. Everest.

One curious result from Wright's photographic observations

relates to the north polar cap. In the violet images the north polar cap appears prominently; in the red images it is a rather inconspicuous object. The dates of the various observations correspond to winter in the northern hemisphere of Mars. If the interpretation of the red and violet photographs is correct, the polar cap of the violet images cannot be a surface phenomenon, but must be an atmospheric one. The evidence from the red images suggests that the fainter object recorded there is a surface phenomenon. It therefore appears that the north polar cap during the Martian northern winter is a double object; if further confirmation is necessary, it is found in the gradual disappearance, as the Martian spring advanced, of the cap in the red images, while the cap in the violet and yellow photographs still remained conspicuous. Now it is unlikely that the atmospheric cap of the violet images consists of clouds similar to our own terrestrial clouds, for these are opaque to red light, and as we have seen, the red photographs record what is evidently a surface feature below the atmospheric cap. Wright suggests that the upper cap consists of a haze of finely-divided particles. The south polar cap, that is, the cap experiencing the southern summer at the time of the observations, it should be added, appears to be a genuine surface marking.

So far we have not referred to temperature conditions on Mars; clearly, if the north polar cap as observed in 1924 (the winter cap) is composed of snow, the temperature in the north polar regions should be well below zero centigrade; and conversely if such a cap "melts" in the succeeding northern Martian summer, the temperature in the northern hemisphere should rise above zero. This argument was submitted to a definite test in 1924 and 1926 by means of the radiometer, a delicate instrument designed for the measurement of feeble heat radiation. The 1924 observations—confirmed in general by the 1926 observations—showed that the temperature of the north polar regions, in the throes of winter, remained fairly constant at $-70°$ C., while in the south polar region, during the advance of summer conditions, the temperature rose to 10° C. As regards the areas at the centre of the disc, that is, areas under the midday sun, the observations gave temperatures of from 10° to 20° C. for the dark areas (the so-called "seas")

and about 15° lower for adjoining bright areas—the continents, or deserts, according to Lowell. The Martian night must be extraordinarily cold, for areas where the sun was near setting gave zero temperature, while areas where the sun had just risen were as much as 45° C. below zero. The low temperatures found for Mars—low as compared with terrestrial temperatures—are in accord with the comparatively low atmospheric density to which reference has already been made. The temperatures so far quoted refer to the solid surface of Mars; the temperature of the atmosphere near the surface must be somewhat lower.

How shall we sum up the long and arduous researches into the physical characteristics of Mars? The planet has an atmosphere, thinner probably than the earth's; the seasonal disappearances and growths of the polar caps suggest the presence of a limited amount of water on the planet's surface, confirmed by the spectroscopic detection of water vapour in the Martian atmosphere by the Lowell astronomers in 1908; temperature observations indicate that Mars, judged by our own terrestrial standards, is at the best a somewhat cold and chilly planet; the seasonal changes observed in the dark areas appear to indicate the existence of some form of vegetation. And what are the "canals"? There is now little doubt as to their objective reality. The theory of artificiality is not seriously maintained to-day, for they vary from broad rather diffuse bands several hundreds of miles in width to the thin almost indistinguishable tracks portrayed by Lowell. Dr. Trumpler, who assiduously observed Mars at the 1924 and 1926 oppositions with the great refractor of the Lick Observatory, states his opinion as follows: "Perhaps the network system of 'canals' should be identified with depressions in the surface which by higher temperature and accumulation of moisture, produce more luxuriant vegetation and thus become visible"—an opinion that seems to bear at least the germ of truth. The earth teems with life of every form, the moon is cold and dead; somewhere in between comes Mars, a decaying world, its evolutionary course nearly run.

We leave Mars with its interesting but partially solved problems and next consider Jupiter, the giant of the planetary family. Jupiter departs markedly from the spherical form,

the polar diameter (the axis about which it spins) being 82,800 miles, and the equatorial diameter 88,700 miles. These distances are, of course, deduced from the observed angle which the respective diameters subtend at the earth, together with the known distance of the planet from the earth at the time of observation. The mass of Jupiter is found very accurately from the observed period of revolution of its satellites and the application of Kepler's third law—it is 1/1047 of the sun's mass and more than the combined masses of all the other planets. Its dimensions and its mass enable us to calculate its density, which is found to be 1·34 times the density of water.

The great glory of Jupiter is its magnificent system of satellites. The discovery of the four great satellites by Galileo in 1610 was amongst the first fruits of the newly-invented telescope, and, as we have seen, this momentous discovery exercised a profound influence on the course of astronomical thought. A fifth satellite was discovered by Barnard in 1892, and the present century has seen the discovery of four more. The last five satellites are minute bodies, insignificant in comparison with the four great Galilean satellites which, with diameters ranging between 2060 and 3580 miles, rival the four inner planets in splendour. The two outermost satellites are at vast distances from Jupiter, revolving in mighty orbits approximately 15 million miles in diameter, and requiring two years to complete a single revolution. But what distinguishes them from the remaining seven satellites and the satellites of the planets which we have so far considered is the direction in which their orbital revolution around Jupiter takes place. We have had occasion to point out the general uniformities observable in the solar system; all the planets revolve around the sun in one and the same direction, and the majority of the satellites revolve around their parent planets in this same direction. The two outermost satellites of Jupiter are exceptions to the rule—they are said to revolve in the retrograde direction.

The four great satellites are easily visible in the smallest telescope—even opera-glasses or binoculars are quite sufficient to reveal them—and their movements provide a very fascinating study. Their periods of revolution around Jupiter range from about 1¾ days to 16⅔ days. Their orbital planes

differ very little from the plane of Jupiter's orbit around the sun, which latter is inclined at a very small angle to the ecliptic. The consequence is that we see the four satellites together with Jupiter roughly in a straight line, and their movements around Jupiter are observed by us as to and fro motions in a line across or behind the planet's disc. Figure 57 shows a typical configuration of Jupiter, and the four great satellites.

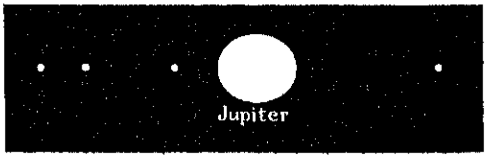



FIG 57.

In Figure 58 the satellites' orbits are drawn so as to illustrate certain interesting phenomena associated with these bodies. The directions of the sun and of the earth are also shown. Now Jupiter is not a self-luminous body, for its brilliance is due to reflection of sunlight. Therefore if a satellite enters the shadow cast by the planet it disappears temporarily from sight—it is, in fact, eclipsed. Satellite I is shown in

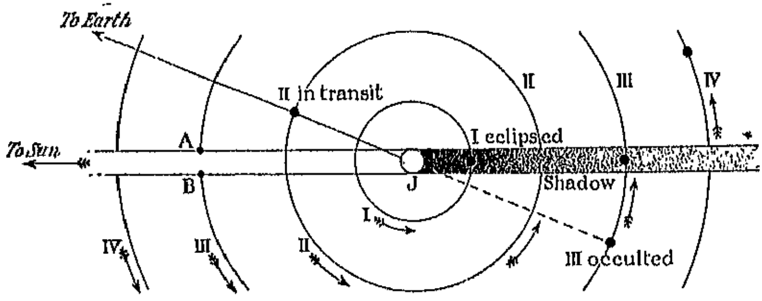


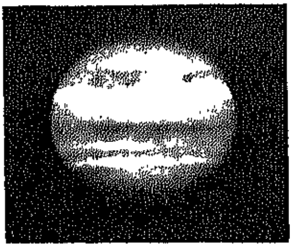

FIG. 58.

Jupiter's shadow. Satellite II is shown in transit, when it is in the act of passing across the disc of Jupiter as viewed from the earth; but as the satellite still enjoys the undiminished light of the sun, this phenomenon is not so easy to observe. The diagram shows another phenomenon—the occultation of a satellite (in the figure it is III); as it revolves round Jupiter it passes behind its disc and is temporarily lost to view. A fourth

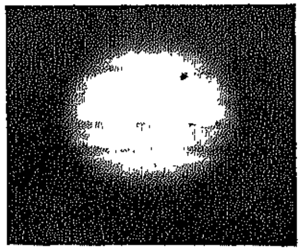
phenomenon, and in some ways the most beautiful, is the transit of a satellite's shadow across the planet's disc. Consider satellite III. When it is between the points A and B (Figure 58) of its orbit, it blocks part of the sunlight which would normally illuminate Jupiter; the satellite, in other words, casts its shadow, which is seen as a small round dot, upon the brilliant globe of Jupiter, and as the satellite revolves in its orbit the shadow moves across the planet's disc.

The continuous observations of the eclipses of Jupiter's satellites led to the laws which governed the phenomena, and therefore astronomers were enabled to predict such occurrences with tolerable accuracy. But observations did not quite satisfy the predictions, for sometimes the eclipse occurred a few minutes too soon and at other times a few minutes too late. Discrepancies in astronomy such as this generally lead to discoveries of far-reaching importance, and the eclipse phenomena of Jupiter's satellites proved no exception to this general rule. It was noticed that when Jupiter was near opposition, that is, when it was nearest the earth, the eclipses occurred before the predicted times, and when Jupiter was at greater distances from the earth than the average, the occurrences were later than they should have been. In 1675 the Danish astronomer Roemer announced the explanation of the apparently erratic behaviour of the satellites. Before this date it was believed that light travelled with infinite velocity; that, in fact, the emission of a light signal and its reception at no matter how great a distance were truly instantaneous. The eclipse of a satellite is just such a signal, and if the velocity of light were infinite the time of its reception (that is, of the observation in the telescope) would be independent of the relative positions of Jupiter and the earth in their respective orbits. Roemer proved conclusively that the observed discrepancies furnished by the eclipse phenomena of the satellites were simply the result of the finite velocity of light, the magnitude of which he was enabled to calculate from the known factors in the problem. Needless to say, his result was merely a rough approximation to the modern value of 186,000 miles per second, for the distance of the earth from the sun, which fixes the scale of the solar system, was then known with little approach to accuracy.

Plate X gives the reader an idea of the appearance of Jupiter in the telescope. The most prominent features are the broad belts of varying shade parallel to the planet's equator; these are not permanent in character. In 1878 a great oval area, at first of a pink colour, developing later into a brick-red marking, became the most prominent feature of the planet; this was the great Red Spot. By 1919 it had almost completely faded away. By means of the visible markings the period of rotation of Jupiter about its axis has been determined; for equatorial regions the period is nine hours fifty minutes, whilst for polar regions the period is about five minutes longer. Jupiter thus resembles the sun in this respect. There is no doubt that our observations of Jupiter are observations of a dense atmosphere, so dense that we are unable to penetrate to the solid surface of the planet, if, indeed, it has a solid crust like the earth. The rotational period is the shortest in the solar system; an equatorial marking on Jupiter is whirled round at the enormous speed of 95 miles per minute. What is the physical constitution of Jupiter? Its density, as we have seen, is $1\frac{1}{3}$ times that of water, which is just about the average density of the sun. Until a few years ago it was generally believed that Jupiter was gaseous like the sun, and at a considerable temperature, but not so hot as to be self-luminous. This latter condition is a necessary corollary of the complete visual disappearance of a satellite during eclipse, for if the planet were even feebly self-luminous the eclipsed satellite would faintly show by means of the reflected light from Jupiter. In 1924, Dr. Harold Jeffreys upset all pre-conceived notions of the physical state of Jupiter. By mathematical reasoning, taking account of the low average density of the planet and certain other mechanical ideas involving the dimensions and shape of the planet, he was led to picture Jupiter as consisting of a rocky core, surrounded by a layer of ice several thousand miles thick, which again was surrounded by an extensive atmospheric shell. Instead of being a comparatively hot body, according to the traditional view, Jupiter is now conceived to be unutterably cold. The recent radiometric measures of the planet's temperature appear to support Jeffreys' contention. It is unnecessary to specify more particularly the arguments put forward by the two opposing schools of thought; the

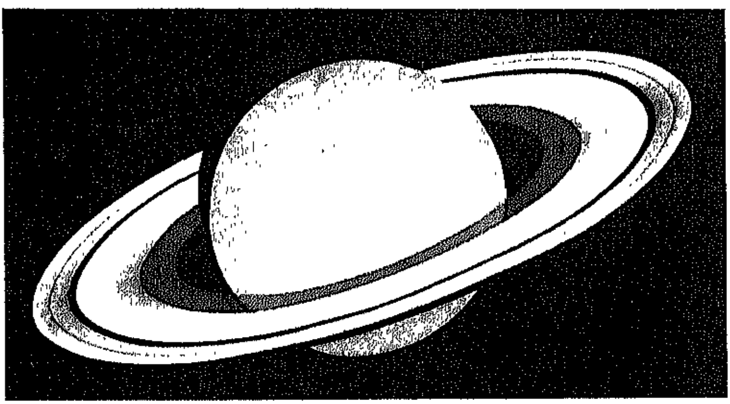


(*a*)



(*b*)

Photographs of Jupiter.
(*a*) in ultra-violet light, (*b*) in infra-red light.
*Lick Observatory.*



(*c*)

(*c*) Saturn. (Drawing by R. A. Proctor.)

reader will probably think it advisable meanwhile to suspend judgment of a subject fraught with such uncertainties, and to consider the physical constitution of Jupiter as yet one more of the unsolved problems of the universe.

In these days we are all familiar with the pleasant pastime —promoted generally by the daily press—of arranging famous authors, or composers, or jockeys in an order of merit, which is finally determined by the cumulative votes of all those interested. If the different celestial marvels were similarly subjected to the arbitrament of the ballot it is practically certain that Saturn with its marvellous and beautiful system of rings would achieve the first place (Plate X). When Galileo surveyed the planets in turn with his feeble and unpretentious telescope, he was struck by the apparently anomalous form of Saturn. At first he thought the planet was shaped like an olive; later its appearance suggested a great globe, flanked by two lesser globes. Two or three years later, Galileo was astonished to find that the two lesser globes, or "stars" as he called them, had disappeared. "Has Saturn, perhaps, devoured his own children?" he plaintively asked. Galileo's mystification was never clarified. It was reserved to Huygens, almost half a century later, to give the true explanation of the appearance and associated phenomena of what we now know to be Saturn's Rings.

Saturn comes next to Jupiter as regards size. It is markedly flattened towards its poles; actually, the equatorial and polar diameters are 75,100 and 67,200 miles respectively. Saturn possesses nine satellites (the outermost one revolves around the planet in the retrograde direction), and consequently its mass can be accurately determined. The average density of the planet is the lowest in the solar system—it is but seven-tenths that of water. The arguments of Jeffreys in relation to the physical constitution of Jupiter apply equally to Saturn. In the telescope there are seen broad and rather faint belts parallel to the planet's equator. The period of rotation is about 10¼ hours—this refers to the planet's equator, and there is a certain amount of evidence that for higher latitudes the period of rotation is somewhat greater; Saturn thus resembles both the sun and Jupiter in this respect.

Let us now return to the planet's incomparable system of

rings. The plane of the rings coincides with Saturn's equatorial plane, and the latter is inclined to the ecliptic at an angle of 27°. At intervals of a little less than fifteen years the rings are presented to the earth edge-ways, and for a day or two even in the most powerful telescopes they are lost to view. This was the phenomenon that so mystified Galileo and later was correctly interpreted by Huygens. Seven and a half years after disappearance or reappearance the rings are seen in their most open aspect, for then the earth is at its greatest possible altitude above the plane of the rings, namely 27°.

As soon as telescopes began to improve in definition, it was seen that the chief glory of Saturn was not a single uniform ring. As early as 1675 two rings were recognised with a dark division between them, called the Cassini division, after the astronomer who first detected it. The outer ring is called Ring A and the inner one Ring B. About ninety years ago Encke discovered a faint division in Ring A, known as Encke's division, and in 1850 Bond and Dawes independently discovered a faint extension of Ring B towards the ball of the planet, known from its dusky appearance as the Crape Ring. Figure 59 shows diagrammatically the structure of the ring system represented as a plan or "bird's-eye view."

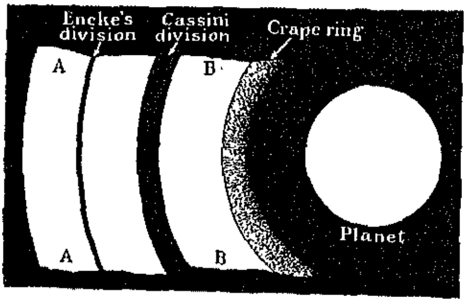


FIG. 59.—SATURN'S RINGS.

What is the constitution of the rings? We have to remember that their visibility as well as that of the ball is due to reflected sunlight. The reader might consider this problem one of the most intractable in the whole of astronomy; we certainly do not know how Saturn came to be endowed with its marvellous rings, but we are, nevertheless, certain of what these rings are made. They consist of a vast assemblage of small discrete bodies, each, in fact, a satellite of Saturn, revolving about the planet in circular orbits. This conclusion can be tested by several methods—observational, mathematical,

and spectroscopic. The crape ring, for example, is semi-transparent, for the ball of the planet can be seen through it, suggesting that the individual satellites of this ring are smaller and less densely packed together than in the other brighter rings A and B. A most interesting observation was made by Captain Ainslie, R.N., in 1917. As Saturn wanders amongst the stars, it is clear that on occasions it will pass in front of particular stars, occulting them, as it is called. Ainslie's observation related to the occultation of a comparatively bright star by the *rings*. The path of the star relative to Saturn took it along the Cassini division and then across Ring A. In Ring A the star was still visible, although much reduced in brightness. When it was in the Cassini division it was practically as bright as when clear of the rings. These observations are consistent with the complex structure of the rings, as stated above, the divisions being merely regions completely, or almost completely, devoid of the minute satellites constituting the rings themselves. In his celebrated Adams prize essay in 1856, Clerk-Maxwell proved mathematically that the rings could not possibly be thin solid sheets nor liquid, for these could not maintain an existence as such under the gravitational forces in play, and he proved that the rings could be stable and enduring only if they consisted of a multitude of tiny satellites. The most conclusive evidence, however, was furnished by the spectroscopic observations of Keeler, made in 1895. If the rings are solid sheets revolving around Saturn the rotational velocity, in miles per second, should increase uniformly from the inner edge of Ring A, for example, to its outer rim. If two people are standing on a rotating turn-table, one at the edge and the other half-way between the edge and the centre, it is clear that the former will describe in one revolution twice the distance described by the latter, for the lengths of the circumferences of the two circles which they describe are proportional to the radii. Accordingly, their velocities tangential to the respective circles are proportional to the length of the radii; that is to say, the velocities increase uniformly outwards from the centre of the turn-table. If, on the other hand, the rings consist of a vast swarm of satellites, the velocities in the different satellite orbits decrease, according to Kepler's Laws, as we go from a smaller orbit to a greater. Keeler submitted these

antagonistic hypotheses to the spectroscopic test provided by Doppler's Principle. He placed the slit of his spectroscope across the ring system, as shown in Figure 60. Effectively, the lines of the spectrum showed that the line of sight velocity of a point X was less than the line of sight velocity of a point Y nearer the centre; in other words, the velocity due to the rotation of the ring decreases from the inner edge outwards. Moreover, the measures showed that the velocity at X, for example, was exactly the velocity in its orbit of a satellite at the distance CX from the centre of the planet. If any doubt existed before 1895 of the constitution of the rings, Keeler's beautiful demonstration dispelled it effectively.

It remains to discuss one more problem: Why are there vacant lanes in the rings—the so-called divisions? In par-

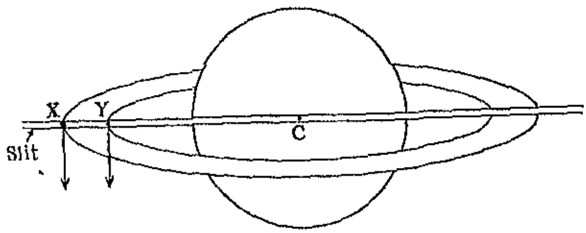



FIG. 60.

ticular, what is the cause of the Cassini division, more than 2000 miles in breadth? The problem is a very complicated one and has been solved by Dr. G. R. Goldsbrough. The motion of any one of the tiny constituent satellites of the rings—we shall refer to it as a particle in distinction to the planet's family of satellites or moons—is governed by the gravitational attraction on the particle of Saturn itself, of the nine known satellites and of the innumerable particles forming the rings. Saturn's influence is, of course, by far the greatest, and if all the other influences were neglected the particle would describe a definite orbit around Saturn. The nine satellites and the ring itself are disturbing influences modifying and changing the orbit of the particle according to well-known mathematical principles. If a particle described an orbit within the Cassini division, for example, such an orbit would be unstable owing to the disturbing action of Mimas (the satellite nearest Saturn), and the

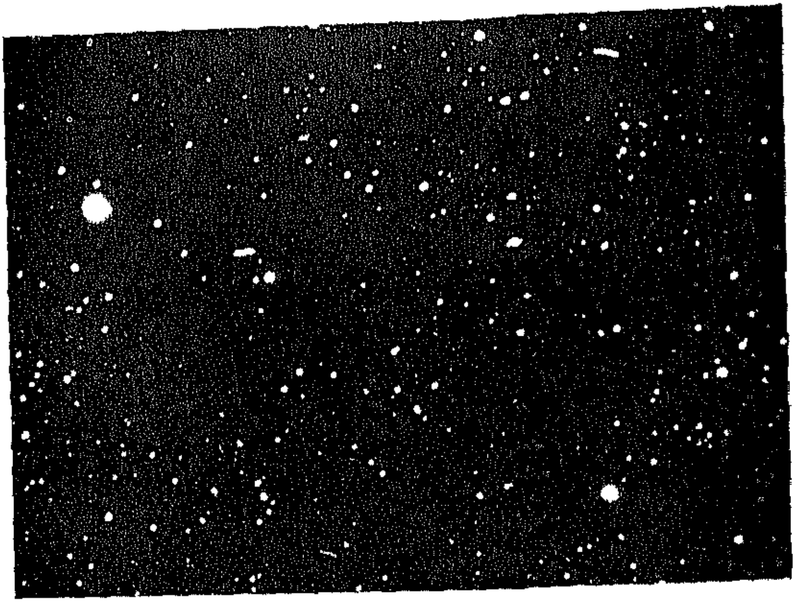
particle would be forced to revolve in an orbit of somewhat different diameter. The absence of particles in the Cassini division is thus ascribed to Mimas. It is hardly necessary to enter into further details; Goldsbrough's beautiful mathematical theory accounts in a most remarkable way, on the lines just indicated, for the different features of the ring-system.

Uranus and Neptune may be dismissed very briefly; the circumstances attending their discovery have already been described. The former has four satellites, moving in the retrograde direction in orbits very nearly at right angles to the plane of the planet's orbit—a very remarkable departure from the general uniform plan of the solar system. Uranus rotates about an axis in a period of about eleven hours. Neptune has one satellite, discovered by Lassell immediately after the discovery of the planet itself; its motion is also retrograde. Neptune marks the outermost limit of the planetary system; its orbit is nearly a circle, of radius 2800 million miles—almost exactly thirty times the distance of the earth from the sun. The time necessary to describe this magnificently great orbit is 165 years; since its discovery in 1846, the planet has therefore moved round but half its orbit.

Up to the present our survey of the solar system has included only the eight great planets with their satellite systems; we now consider the numerous groups of planets, in size almost insignificant in comparison with their more famous brethren, known as the Minor Planets. If the reader refers to Figures 5 and 6 he will notice that there is a very much greater gap between the orbits of Mars and Jupiter than between the orbits of, say, the earth and Mars. Both Copernicus and Kepler had noted the wide separation of the two orbits of Mars and Jupiter, and the latter had seriously speculated on the fate of a planet that, he imagined, had once occupied an orbit intermediate between the orbits of these two planets. In the eighteenth century, astronomers were familiar with an empirical law known as Bode's Law, which is as follows. Write the numbers 0, 1, 2, 4, 8, etc., doubling each in succession; multiply each of these by 3, and to each product in turn add 4; the results are shown in the second line in heavy type.

| Mercury. | Venus. | Earth. | Mars. | | Jupiter. | Saturn. | Uranus. | Neptune. |
|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 4 | 8 | 16 | 32 | 64 | 128 |
| **4** | **7** | **10** | **16** | **28** | **52** | **100** | **196** | **388** |
| 3·9 | 7·2 | 10 | 15·2 | | 52·0 | 95·4 | 191·9 | 300·7 |

If the earth's average distance from the sun is denoted by 10 units, then Bode's Law states that the figures in heavy type are approximately the average distances from the sun of the planets then known (the names of these planets are given in the appropriate columns, and their actual distances—on the scale referred to above—are shown in the last line; the corresponding figures are also given for Uranus and Neptune, which had not yet been discovered). It must be confessed that the correspondence between the second and third lines is, if not mathematically exact, yet, nevertheless, striking. In 1781 Uranus was discovered, and, as the numbers above show, the new planet fitted very well into the scheme. In consequence, astronomers began to think seriously that there might be something after all in Bode's Law. They saw the gap in the sequence between Mars and Jupiter and, conviction stimulating action, some of them set about the business of discovering the hypothetical planet, first forming themselves into the "Society for the detection of a missing world," consisting of twenty-four members! They searched the zodiac diligently, but the "missing world" evaded all the efforts of the astronomical detectives. On January 1, 1801, the Italian astronomer, Piazzi, who was engaged in the routine work of observing star-positions, gained—as it were by accident—the prize that had for so long eluded the grasp of his more systematic colleagues. The new planet was named Ceres. A certain number of observations of its positions on various dates were made successfully, but soon it was lost, owing to its conjunction with the sun. But these observations were sufficient to enable Gauss, a young German mathematician, to calculate its orbit and so to predict its position on any future date. In due course Ceres was rediscovered. Although Ceres was found to fit into the scheme suggested by Bode's Law, its discovery did not afford complete satisfaction, for it was such an insignificant body; the modern



(*a*) Three Minor Planet Trails.
*Prof. M. Wolf.*

(*b*) Photograph of Exploding Meteor.
*Mr. C. P. Butler.*

measures fix its diameter at 480 miles, about one-fifth the diameter of Mercury. When Olbers discovered a second minor planet (Pallas) in 1802, he re-introduced the idea that originally a much greater planet had occupied the vacant orbit between Mars and Jupiter, which, by explosion or disruption of some kind, was shattered into numerous fragments, of which Ceres and Pallas were the first to be detected. By 1807 two more had been discovered; the fifth was discovered in 1845, and since then the number of discoveries has increased by leaps and bounds. Up to 1891 the method of searching for minor planets was the very laborious one of making a survey of a particular part of the heavens on two or more successive nights; if one of the star-like objects was detected to have altered its position relatively to the stars in the course of a day or two, the object was a new member of the solar system. In 1891 photographic methods were first employed by Dr. Max Wolf of Heidelberg. The telescope is driven to follow the stars accurately; in consequence, their images on the photographic plate are circular in shape; but a minor planet which is moving with reference to the stars will reveal its presence by a short trail on the plate, the length of the trail depending on the duration of the exposure and the rate at which the planet is moving with reference to the stars. Plate XI (*a*) is a reproduction of a photograph on which the trails of three minor planets are clearly visible. From a sufficient number of observations, the orbit of a newly-discovered minor planet can be calculated, and it is thereafter securely held in the net of mathematical analysis.

In 1926 no less than 115 minor planets were discovered, all extremely faint objects; the diameters of the feeblest can hardly exceed two or three miles. Up to the end of 1926 the number of known minor planets was close on 2000—of these Dr. Wolf has discovered more than 500. The planets are given a number according to the date of discovery, and most of those up to 900 and several beyond this number have been given names. Nos. 1000, 1001, 1002 are named Piazzia, Gaussia, Olbersia, in commemoration of the three distinguished astronomers associated in the first discoveries of minor planets. With one or two exceptions the orbits of the minor planets are scattered between the orbits of Mars and Jupiter.

The most interesting group of minor planets is the "Trojan" group, consisting at present of six members—Achilles, Hector, Nestor, Agamemnon, Patroclus, and Priamus—all at about the same average distance from the sun as Jupiter. In Figure 61 the orbit of Jupiter is drawn; A and B are two points forming the vertices of two equilateral triangles, with the sun and Jupiter as base. Four of the Trojans (the first four above) are in the neighbourhood of A, and the remaining two in the neighbourhood of B. As Jupiter revolves around the sun, so also do the six Trojans, maintaining approximately the double equilateral configuration.

In all ages comets have inspired terror and fear of impending catastrophe; the superstitious see in the magnificent naked-eye comets portents of woe, of widespread disaster and the fall of the mighty from their seats. It is recorded of the great comet of 1456 that the Christian world was convulsed with terror at its apparition, and that the Pope ordered prayers to be said for protection against the terrifying visitor, coupling the latter with the Turks, the dreaded foes of Christendom. The great comets have a threefold structure—the head (a diffuse nebulous condensation), the nucleus (a bright stellar-like point near the middle of the head), and a tail, which may extend for millions of miles. Plate XII contains a photograph of Halley's comet at its apparition in 1910, and of Morehouse's comet, which appeared in 1908. Of all the comets, that which bears the name of the great astronomer Halley is perhaps the most famous. Before Halley's time comets were regarded as chance visitors, arriving mysteriously within the near confines of the solar system and as mysteriously departing to unknown regions of space. In 1682 a great comet appeared; Halley was led to associate it with the great comets of 1607 and 1531, and to affirm that it was a member of the solar

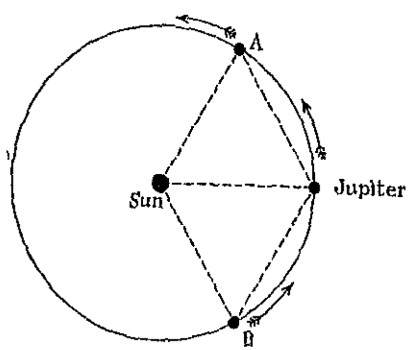


Fig. 61.

system revolving around the sun in a period of about seventy-five years. Halley predicted its return in 1758—a prediction that was duly fulfilled—and its later apparitions (the last in 1910) have been in accordance with Halley's period. The return of the comet in 1910 evoked the following from a distinguished astronomer :—

"Of all the objects in the sky
There's none like Comet Halley :
We see it with the naked eye
And periodically.
The first to see it was not he
But still we call it Halley
The notion that it would return
Was his originally."

A remarkable comet was that known as Biela's comet (we use the past tense purposely). Towards the end of 1845 it returned, according to prediction, displaying the usual features


FIG. 62.—DRAWING OF DAYLIGHT COMET (1910a).

of a large comet. But in January of the following year it was seen to divide up into two parts, a celestial catastrophe unprecedented in the history of astronomy. At the next return, in 1852, the comet was still divided, but the gap between the two sections was now very much greater. In 1858-9 it was eagerly looked for, but the comet had vanished (we shall see later what happened to it).

The great comet of 1910 (known officially as comet 1910a) was so bright when it reached the neighbourhood of the sun that it was easily visible in broad daylight. Figure 62 is a reproduction of a sketch of the comet (with the sun) made under these circumstances.

Planetary orbits are approximately circular; the orbits of comets, on the other hand, are generally very much elongated. Figure 63 represents the orbit of Halley's comet with reference to the orbits of the planets. At its nearest approach to the sun in 1910, the head of Halley's comet was but a few million miles from the sun ; in 1948, when half its period will be run, it will be well outside the orbit of Neptune at a distance

from the sun of between three and four thousand million miles. A further feature of the orbit is that it is described in the retrograde sense; that is, the comet revolves round the sun in a direction opposite to that in which the planets revolve. There are five other comets whose orbits reach out to near or just beyond the orbit of Neptune—these form a group known as Neptune's family of comets. Jupiter's family is the most numerous; about fifty are so far recognised, with periods ranging from 3·3 years (the period of Encke's Comet) to about 8 years.

Nothing is known precisely about a comet's mass except that, in comparison with the usual order of planetary masses, it must be practically negligible. This is surprising in view of the enormous bulk of the great comets with diffuse heads,

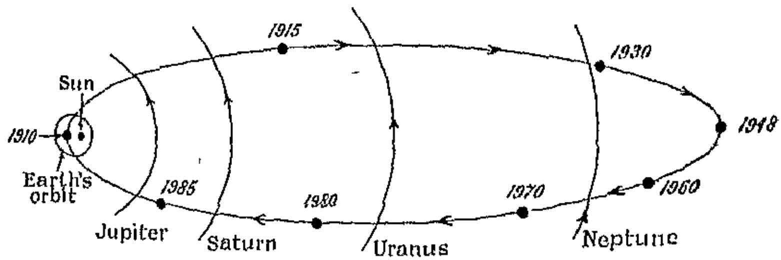
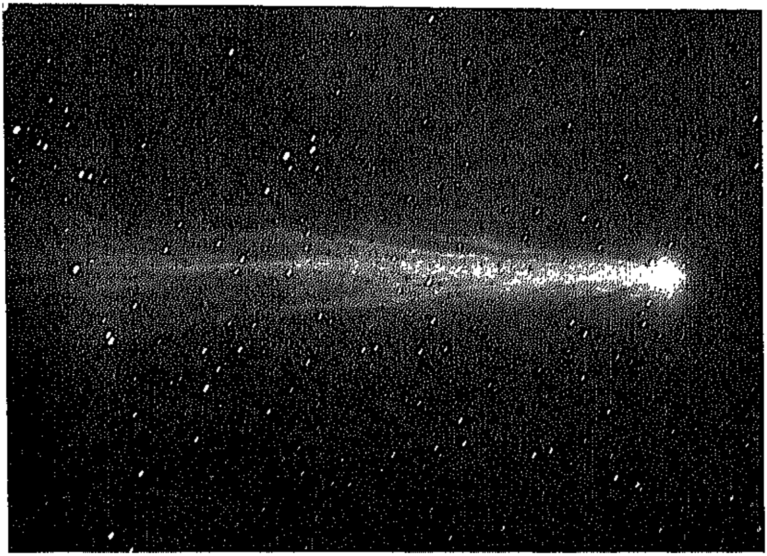



Fig. 63.—Orbit of Halley's Comet.

sometimes hundreds of thousands of miles across, and tails that may stretch for distances comparable with the diameter of the orbit of the earth or even of Mars. A comet with a mass equal to that of the planet Mercury, for example, would, in making a comparatively near approach to a planet such as Mars, leave an unmistakable imprint on the orbit of Mars; no such effects on the planetary motions have ever been observed, and the conclusion is irrefutable that cometary masses are exceedingly small—probably, at the most, not more than one millionth part of the earth's mass.

The glory of a comet is its tail, and the most remarkable feature of the tail is that it always points away from the sun. The small mass of the comet and its great expanse must mean extreme tenuity of the matter composing the tail, and the direction of this member relatively to the sun suggests some kind of solar repulsion. Such a repulsion is found in the pressure



(*a*) Morehouse's Comet (1908).
*Prof. M. Wolf.*

(*b*) Halley's Comet (1910).
*Union Observatory, Johannesburg.*

of light on minute particles. But is the pressure of the solar radiation sufficient to account for the shape of the tail and the movements observed to take place in it? Here we reach a deadlock, a point beyond which astronomy has not succeeded yet in advancing. Light pressure is most probably an important agency, but it does not, by itself, solve the problem of the structure of a comet's tail.

Whence does a comet derive its light? Cometary spectra show, in the first place, the usual characteristics of the solar spectrum, indicating that part of a comet's luminosity is due to reflection of sunlight by the tiny particles of which it is composed and, in the second place, certain bright bands, due principally to carbon compounds, suggesting that the comet is partly self-luminous. All comets are not constituted alike, but if we regard comets as a whole the available evidence points to the existence of certain hydrocarbons and of carbon monoxide in the tails, and of cyanogen, sodium and iron, as well as the hydrocarbons found in the tail, in the cometary heads. In addition, there are other bands of unknown origin.

Most of the preceding discussion has reference to the brighter comets, most of which are magnificent naked-eye objects. Many of the fainter comets, seen only in large telescopes, however, do not possess the distinguishing feature—namely the tail—of their more spectacular brethren. On the average, about half a dozen of these faint telescopic objects appear every year; according to Dr. Crommelin, 1925 holds the record with a total of eleven, most of which represent new discoveries.

We discuss now very briefly meteors, known popularly as "shooting stars." These are generally very minute bodies which, entering the earth's atmosphere with high velocities, are rendered incandescent by friction, and perish rapidly in a streak of glory. The earth's orbital velocity is $18\frac{1}{2}$ miles per second, so that if a meteor meets the earth in a head-on collision, the meteor's speed relatively to the earth must be greater than $18\frac{1}{2}$ miles per second. As a rough average, we may take 25 miles a second as the speed of a meteor entering the earth's atmosphere. A meteor thus possesses a vast amount of energy of motion which, during the meteor's brief experience of our atmosphere, is converted into heat and light by the frictional resistance of the air. A meteor of the size of a cricket ball has

enough energy to convert 5000 lb. of water at ordinary temperature into steam, and the remarkable brilliancy of meteors must be due to the vaporisation of the meteoric substance at temperatures of several thousand degrees. It is, therefore, somewhat surprising at first sight that the magnificent meteoric displays are produced by particles generally no larger than a pea. Occasionally, a meteor of surpassing brilliancy is accompanied by a noise as of a thunder-clap. Plate XI (*b*) is a photograph which Mr. C. P. Butler, of Cambridge, was fortunate to secure of a very brilliant meteor, and which clearly reveals a disruptive explosion. More infrequently still, meteors, from several pounds to a few tons in weight, succeed in penetrating our

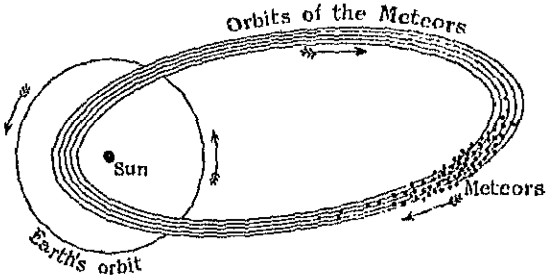



FIG. 64.

atmosphere—these "stones from heaven" are known as meteorites—and, their celestial wanderings thus summarily ended, are laid to rest in the glass cases of our great museums.

On any fine moonless night a stray meteor or two may generally be seen; on rare occasions the watcher of the skies is rewarded with a meteoric display of surpassing grandeur, and the heavens for hours are streaked with the blazing trails of hundreds and thousands of meteors. There are many historical records of great displays. For example: "In the year 599, on the last day of Moharrem, stars shot hither and thither and flew against each other like a swarm of locusts; people were thrown into consternation and made supplication to the Most High." The records show that the showers are periodic, and the explanation is in terms of a great shoal (or shoals) of meteors moving in a great orbit under the controlling influence of the sun. Figure 64 represents the orbit of the earth and that of one of the meteor swarms.

At certain times when the earth crosses the track of the meteors it encounters the main shoal, and the result is a meteoric bombardment. A year later the earth is again at the intersection of the orbits, but now the majority of the meteors have reached a different part of the orbit, and it is only the laggards that crash into our atmosphere and provide a moderate display. The interval between the successive maximum showers fixes the period of revolution of the main shoal. There are several meteor swarms, each with its own distinctive period. There is, for example, the "Leonid" shower, with a period of thirty-three years; the earth crosses the meteor track about November 14. If the meteors were actually bunched together, meteoric showers would, of course, only occur at intervals—in the case of the Leonids—of thirty-three years. But every year produces a minor display about November 14, showing that there are meteors spread out along the great orbit; just as runners in a long distance race become strung out along the track, so the original body of meteors slowly loses its compact form. The number of individual meteors must be prodigious; it is estimated that during one of the great displays the earth netted meteors at the rate of 75,000 per hour. This wastage cannot go on for ever, and if the orbit of the Leonids, for example, remains unchanged, the earth and the planets must eventually sweep up practically the whole of this great swarm.

We have already referred to the break-up and disappearance of Biela's comet. The orbit of this comet was, of course, definitely known. It is significant that in 1872, when the comet was due back to the neighbourhood of the sun, a magnificent display of meteors occurred, from the circumstances of which it was found that the orbit of the meteoric swarm coincided with the orbit of the defunct comet. These meteors are known as the "Andromedids." This and subsequent showers seem to point, beyond a peradventure, to the meteoric constitution of the comet—in part, at least.

Despite its cosmic insignificance, a meteor flashing into the earth's atmosphere offers the means of estimating the extent of the earth's gaseous envelope. If several observers, at different stations, observe the track of the meteor with reference to the background of stars, the combined observations lead to the height above the earth at which the meteor first becomes

luminous and the height at which the frictional resistance of the air has completed its work. The first height is that at which the atmosphere is just effective in making the meteor luminous; this height is found to be about 100 miles. For the great majority of meteors, the height at which combustion is completed is from about 20 to 40 miles. We conclude from the evidence afforded by meteors that the terrestrial atmospheric shell extends to a height at least of 100 miles above the earth's surface.

# CHAPTER VIII

## THE STARS

LIFE in our great modern cities, which are so brilliantly illuminated by artificial light as soon as the sun sinks in the west, does not make such close and friendly contact with the starlit sky as in past ages, when the face of the heavens was to man an open and familiar book. To the wandering tribes of the desert, to the shepherds "watching their flocks by night," to the sailors in their sleepless vigil, the stars were ever faithful and constant friends, known and called by familiar names. Star-names, as they have come down to us through the ages, are almost entirely Arabic and Greek and Latin in origin. Pastoral and personal elements characterised the Arabian nomenclature; in the former category were stars designated by the names of the common objects of their daily experience, such as wells, tents, mangers, fruits, etc., and in the latter were stars described adjectively as "faithful," "neglected," "trusty," "solitary," etc. The Greek and Latin star-names, on the other hand, bear the names of their mythological heroes and characters; for example, Castor, Pollux. The Greeks, moreover, grouped the stars into constellations, and to these were given the great names in their mythology (for example, Hercules, Andromeda, Cassiopeia, etc.), and the names of animals (for example, Bear, Lion) and objects, such as the Scales, Northern Crown.

It is difficult to trace any apparent resemblance between the constellations and the heroes or objects after which they were named according to the imaginative fancies of the early observers of the heavens. Occasionally, as in the constellation "Corona Borealis"—the northern crown—the arrangement of stars does suggest the object named; in the constellation of Orion, too, it is easy to picture the general outline of the mighty hunter with prominent stars marking his shoulders, belt and sword, etc.

The writings of Ptolemy preserve for us the star-catalogue of the Greek astronomer Hipparchus, who flourished in the second century B.C., which contains a list of forty-nine constellations (visible in Greece) with over a thousand stars. Of Hipparchus, a later writer records: "The same man went so far that he attempted (a thing even hard for God to perform) to deliver to posterity the just number of the stars." We shall see later that the observations of Hipparchus bore substantial fruit in the eighteenth century. To-day, astronomers recognise eighty-eight constellations, dividing the entire sky into eighty-eight sections. The northern constellations follow, in the main, the delimitations of the early Greek astronomers. Attempts have sometimes been made to abandon the arbitrary division of the sky and to replace it by a uniformly-planned dissection—but without avail; as regards the constellations, modern astronomy is still the actual and direct legatee of mythological philosophy.

The brightest stars of a constellation are distinguished by means of a system introduced by Bayer at the beginning of the seventeenth century. For example, the brightest star of the constellation Orion is called $\alpha$ Orionis, the next in brightness $\beta$ Orionis, and so on throughout the Greek alphabet, on the exhaustion of which Roman letters are brought into use. The extreme limitations of this system are obvious when attention is directed to the vast number of stars revealed by the telescope outside the range of naked-eye observation. The system was extended in application by Flamsteed—the first Astronomer Royal—who allotted numbers to the telescopic stars of a constellation without disturbing the nomenclature of the brightest stars which continued to retain their Greek and Roman letters.

We have seen in earlier chapters that the plane of the ecliptic—defined by the orbit of the earth around the sun—differs very little from the orbital planes of the other planets. As viewed from the sun, the earth would be seen to trace out a great circle on the celestial sphere, in the course of a year, with reference to the stars. In the same way, were one able to see the stars during the day, it would be found that the sun apparently makes an identical circuit of the stars, in the course of the year, as viewed from the earth. This circuit is the ecliptic. The major planets and the moon are always found

within 9° of the ecliptic, and this narrow belt of the celestial sphere is called the Zodiac, divided into twelve constellations, equally spaced along the ecliptic. The twelve zodiacal constellations[1] are:—Aries, Taurus, Gemini, Cancer, Leo, Virgo, Libra, Scorpio, Sagittarius, Capricornus, Aquarius, Pisces. The constellation in which the sun is on a particular day is easily found by observation. For example, if there is a full moon, and the moon is in the 3rd constellation, *i.e.* in the constellation Gemini (the Heavenly Twins), then the sun must be on the opposite side of the ecliptic in the 9th constellation, *i.e.* in the constellation Sagittarius (the Archer). Failing a full moon, if the zodiacal constellation, which is south at midnight, is observed to be, say, the first, *i.e.* Aries, then the sun is in the 7th, *i.e.* in Libra.

The earliest attempts to apply photography in the service of astronomy were made in 1850. The principle is extremely simple: the eye-piece of the telescope is removed and replaced by a holder carrying the photographic plate, which, securely held in position, can then be exposed to the light of the stars. The first success—that of photographing the bright star Vega—was rapidly extended, until in 1857 the images of the faintest naked-eye stars could be recorded on the photographic plate. The great possibilities of photography in relation to stellar astronomy were early appreciated, but its successful application had to await the requisite improvement in photographic processes. The invention of the "dry-plate" should have suggested immediately the new instrumental power ready to be applied to the study of the heavens, but it was almost, as it were, by accident that the introduction of photography into the realm of practical astronomy became an accomplished fact. In 1882 a great comet appeared, a wonderful spectacle, especially in the southern hemisphere. Cameras were then not uncommon, and several photographers in South Africa attempted to photograph the comet. Unless the camera were made to follow

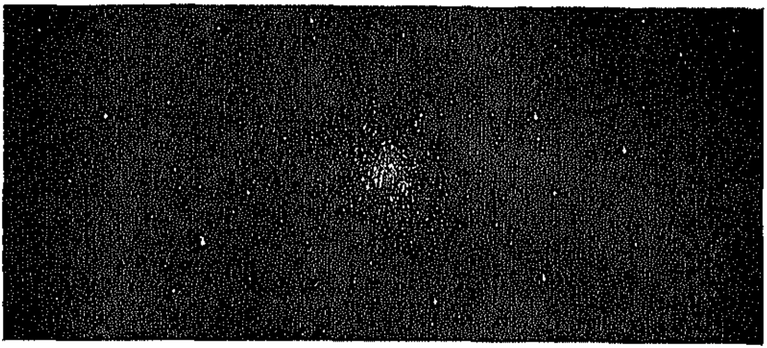
[1] The following well-known lines are an aid to the memory:—

"The Ram, the Bull, the Heavenly Twins,
And next the Crab the Lion shines,
The Virgin and the Scales,
The Scorpion, Archer, and He-Goat,
The Man that bears the watering pot
And Fish with glittering tails."

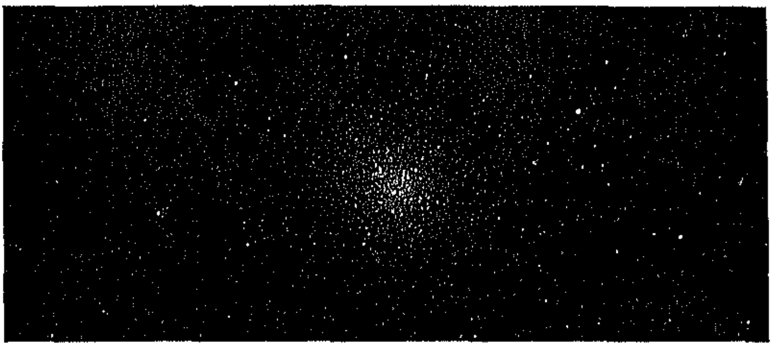
accurately the diurnal motion of the comet across the sky, such attempts, for which a long exposure is necessary, could be in general of no scientific value; but what they did reveal was the possibility that the comet might be photographed successfully provided that it could be followed accurately during the hour or two necessary for a satisfactory exposure. The astronomical telescope, with its accurate mechanism for following the heavenly bodies as they move across the sky, supplied the means. Accordingly, on the suggestion of Sir David Gill, a camera was strapped on the tube of the 6-inch equatorial of the Cape Observatory, and several beautiful photographs of the comet were secured in October and November, 1882, with exposures varying between half an hour and two hours. The photographs, however, showed more than the comet; they bore the images of hundreds of stars. So was foreshadowed, if not actually begun, the revolution in practical astronomy.

The advantages of stellar photography over visual observational methods are almost self-evident. A photographic plate is a permanent record of the positions of the stars at the time the plate was exposed; these positions can be measured at leisure with an accuracy far surpassing that of the visual observations; of great importance, too, is the resultant economy in time, in contrast with the slow and tedious eye-observations. But the great power of photography is a consequence of the long exposures which can be made. The eye records instantaneous impressions stimulated by the light of a star; the photographic plate, on the other hand, adds up throughout the exposure all these instantaneous light stimulations and, the longer the exposure, the greater is the effect on the plate. Moreover—and this is the important result—the longer the exposure the fainter are the objects whose images can be recorded on the plate. The three photographs of the same star-cluster, with different exposures, illustrate this feature in a remarkable way (Plate XIII).

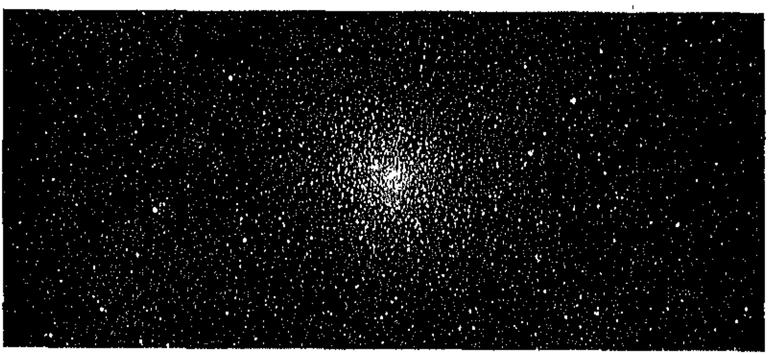
One star differeth from another in glory and, from the time of Ptolemy onwards, the problem of grading the stars according to their brightness has demanded the continuous attention of astronomers. Ptolemy divided the visible stars into six "magnitude" classes; the fifteen brightest stars were said to be of the first magnitude, the next fifty in bright-



(*a*) Exposure 5 minutes



(*b*) Exposure 50 minutes



(*c*) Exposure 90 minutes
Three Photographs of the Star Cluster M. 22 in *Sagittarius*.
*Lick Observatory.*

ness of the second magnitude, and so on until in the sixth magnitude class were stars just visible to the naked eye. The accurate classification of the myriads of stars, visual and telescopic, according to brightness, evidently requires to be based on more definite and exact principles, and now *magnitude* has come to mean a number signifying, on a certain scale, the brightness of a star. The scale is as follows. A star A which is 100 times brighter than a star B is said to be 5 magnitudes brighter than B. For example, if the magnitude of A is denoted by 1·0, then the magnitude of B is denoted by 6·0. Again, if B is 100 times brighter than a star C, the magnitude of C is denoted by 11·0. As a difference of 5

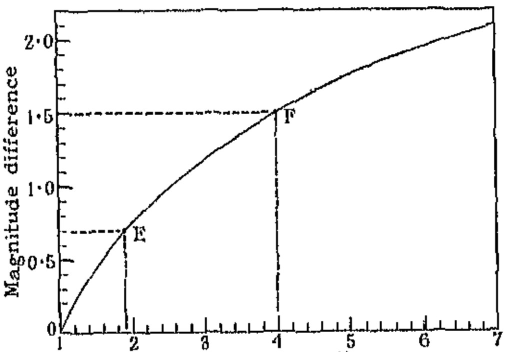



FIG. 65.

magnitudes corresponds to relative brightness in the ratio of 100 to 1, then the brightness of A (magnitude 1·0) will be 100×100, or 10,000 times the brightness of C (magnitude 11·0). In other words, the star A is equivalent as regards brightness to 100 stars each of the brightness of B and equivalent to 10,000 stars, each of the brightness of C. The ratio of brightness corresponding to a difference of 1·0 in the magnitudes of two stars is 2·512; that is to say, the brightness of the star A (magnitude 1·0) is a little over 2½ times the brightness of a star D, whose magnitude is 2·0. It will be seen later that the ratio of brightness can be accurately measured, and consequently the sub-division can be carried as far as is consistent with the capabilities of the measuring apparatus.

The relation between brightness ratio and the magnitude difference from 0·0 to 2·0 is illustrated in Figure 65. It will be

seen—looking at the point E on the curve—that brightness ratio of 1·9 corresponds to a magnitude difference of 0·7, and for the point F on the curve, the brightness ratio of 4·0 corresponds to a difference in magnitude of 1·5. It remains to assign to one star a magnitude number, and when this is done the magnitude of any other star can be assigned from the measured brightness ratio. On the visual magnitude scale adopted in practice, the magnitude 1·0 corresponds very nearly to the bright stars Altair and Aldebaran; the former is a little brighter, the latter a little fainter, than magnitude 1·0. The magnitude of Capella is 0·2; Sirius, the brightest star in the sky, is 5·2 times brighter than Capella, and from Figure 65 the magnitude difference is seen to be 1·8; the magnitude of Sirius is thus 0·2−1·8, or −1·6. Canopus is the only other star with a negative magnitude (−0·9).

Until recent times magnitudes were entirely the result of estimation by eye at the telescope. In the modern observatory optical, photographic and physical appliances are all brought into the service of astronomy to determine with the utmost precision the relative amounts of light and heat energy radiated by the stars. Accordingly, there are several magnitude systems which depend on the nature of the radiation measured by the various kinds of instruments. We shall describe these briefly.

1. *Visual Magnitudes.*—In Chapter VI we have learned that the sun radiates heat and light which can be split up into elements, each with its own appropriate wave-length, and that it is only to a portion of the total radiation that the eye is sensitive, namely, to that range of the spectrum which in its complete blending corresponds to what we call white-light. So it is with the stars, and so when we make a comparison—with the naked eye—of the relative brightness of two stars we are, in fact, measuring the ratio of the quantities of that radiation to which the eye is sensitive emitted by the two stars.

Two methods have been employed in the past to measure the visual magnitudes of the stars.

In the first, the pole star and the star to be compared are brought into the same telescopic field of view by means of an optical arrangement, into the details of which we need not

enter here. By means of an optical device the brightness of Polaris is reduced to apparent equality with that of the star, and from the known optical principles of the apparatus the ratio of the brightness of Polaris to that of the star is deduced; then by calculation, or by means of a curve as in Figure 65, the difference in magnitude of the two stars is obtained. If it is found from observations made with a photometer—as such an instrument is called—that Polaris is, say, 1·9 times brighter than the star, then from the curve the magnitude difference is 0·7; as the visual magnitude of Polaris is 2·1 on the magnitude scale adopted the star's visual magnitude is then 2·1+0·7, or 2·8. In this way the visual magnitudes of the brighter stars have been measured.

In the second method an artificial source of light is employed—in place of Polaris—as a standard with which the stars are compared in turn as in the previous method.

2. *Photographic Magnitudes.*—When a photograph of a star-region is examined it is evident that the largest images are those of the brightest stars and the smallest images those of the faintest stars. This direct relation between the diameters of stellar images and the relative brightness of the stars concerned forms the foundation of one of the methods of the precise measurement of photographic magnitudes. The ordinary photographic plate, as is well known, is more sensitive to blue light than to red light, and if we photograph, on the same plate, two stars which appear to be of the same visual brightness, we shall find that the diameters of the images will not be quite equal unless the colours of the two stars are the same; a bluish star will record a much larger image, on the ordinary plate, than a reddish star which, to the eye, appears to be of the same brightness as the former. Evidently, too, photographic magnitudes deduced from the measurement of stellar images will depend on the kind of photographic plate employed, so that standardisation of plates is essential; there are many technical difficulties to be encountered, but we need not concern ourselves with these here.

By giving two exposures, on the same plate, each of the same duration, one with the full aperture of the telescope and the other with—let us say—two-fifths of the full aperture, the diameters of any pair of images will then correspond to two

photographic magnitudes with the magnitude difference[1] of 1·0; in this way the magnitude scale can be determined, and we can say, for example, that a star A is 2·7 magnitudes brighter, photographically, than a star B. The measures, however, do not fix the photographic magnitude of A or of B, but only the magnitude difference. The actual values which we call the photographic magnitudes can, consequently, be deduced from the diameter-measures of the stellar images provided that we can define the photographic magnitude of a single star; this is done by assigning as the photographic magnitudes of a certain class of star (technically, of spectral type A0) the values that these stars have on the visual scale of magnitude.

The procedure outlined above has been carried out with great care and precision for a field of selected stars around the north pole of the celestial sphere. The faintest stars are of the 20th photographic magnitude, and the selection is made so as to provide a step-by-step sequence in magnitude; these stars form the "North Polar Sequence." The convenience of having a standard group of stars which can be photographed on a single plate and of which the photographic magnitudes have been accurately determined is evident immediately. Let us suppose that the photographic magnitudes of the stars in the immediate vicinity of Capella are required. These stars are photographed—let us say—with an exposure of thirty minutes. If the stars of the North Pole Sequence are also photographed on the same plate and with the same exposure, then the two sets of images can be directly compared, so that the photographic magnitudes of the Capella stars are obtained with comparative ease.

3. *Photovisual Magnitudes.*—These are essentially equivalent to visual magnitudes, but they are derived photographically. The methods already described of deducing visual magnitudes allow only the examination of one star at a time; in addition, they are incapable of dealing satisfactorily with any but the bright stars. These are disadvantages which do not belong to the photographic method already described.

[1] The ratio of the intensities of the stellar light forming the two images is the ratio of the apertures, *i.e.* 2·5; this is the ratio which defines the unit magnitude interval.

Photovisual magnitudes are found as follows: in front of the photographic plate is placed a yellow filter, which allows only the yellow light of the stars to pass through, cutting off, in particular, that part of the radiation which affects most strongly the ordinary photographic plate. Special plates are used, sensitive to yellow light. The light which passes through the filter and affects the photographic plate is practically of the same wave-lengths as those to which the eye is most sensitive; thus the star-images yield finally what are virtually visual magnitudes; they are designated photovisual magnitudes.

The difference between the visual magnitude (or photovisual) of a star and its photographic magnitude is called the *colour-index* of a star. A red star, of visual magnitude 4·0 say, will be apparently much fainter photographically, so that its photographic magnitude would be denoted by 5·5, for example; the star's colour-index is then denoted by +1·5, which in this instance may be regarded as a measure of the redness of the star. In the same way a blue star would register a somewhat larger image than a white star of equivalent visual brightness: its colour-index is then −0·3, say, which may be regarded as a measure of the blueness of the star.

4. *Photo-electric Magnitudes.*—Another method of measuring relative light intensities is the photo-electric method. When light is allowed to fall on certain metals, such as sodium, potassium and rubidium, electrons are emitted in numbers proportional to the intensity of the incident light. Accurate instruments are available for measuring the relative number of electrons emitted by the photo-electric metal owing to the light action of two stars A and B; hence the ratio of the light intensities of A and B is determined. On the same principle as for visual and photographic magnitudes, a ratio of 100 to 1 in light intensity is defined to indicate a difference of 5 magnitudes. The light, to which the photo-electric effect is due, is of different wave-lengths from that which affects the eye and also from that which affects the photographic plate; accordingly, photo-electric magnitudes are not directly comparable with either visual or photographic magnitudes. Very great accuracy can be attained by this method, and it is employed principally for the detection and measurement of the light

changes in variable stars, to which reference will be made in Chapter XIV.

The three methods—visual, photographic, and photo-electric—are concerned with different wave-lengths of a star's radiation, and consequently no one of the three gives a true account of the ratio of the total radiation emitted by a star A to the total radiation emitted by another star B. Magnitudes which refer to the total amount of stellar radiation are called bolometric magnitudes.

We come now to a preliminary discussion of the causes which, in combination, account for the marked diversity in the apparent brightness of the stars. There is, firstly, the question of relative stellar distances. If, for example, the bright star Capella were removed further from us, it would then appear fainter than it appears at present. The relation of brightness to distance is a simple one; if we imagine that Capella were removed successively to twice, three times . . . ten times its present distance, its brightness would be successively $\frac{1}{4}$, $\frac{1}{9}$ . . . $\frac{1}{100}$ of its present brightness. Now when we determine the magnitude of a star, on the visual or photographic or any other scale, we are merely comparing its brightness—as it appears to us—with the brightness of a standard object, stellar or terrestrial, and the question of the star's distance has nothing to do with our measurements and calculations. Such magnitudes are denoted adjectively as "apparent"—*apparent visual*, apparent photographic, etc. If the stars were identical in every respect, it is clear from our reference to Capella that the relative brightness of two stars A and B—or, what amounts to the same thing, the difference in apparent magnitude—would indicate precisely their relative distances from us. If the apparent visual magnitude of A is 4·3 and that of B is 9·3 (a difference of 5 magnitudes), then A appears to our eye 100 times brighter than B, and still assuming that A and B are identical in every way, we deduce that B is at 10 times the distance of A. Let us state the matter somewhat differently: suppose A to be removed to 10 times its present distance from us; its apparent brightness is now only one-hundredth of its original brightness and its apparent magnitude is now denoted by 4·3+5·0, *i.e.* 9·3. Thus a distance ratio of 1 : 10 corresponds to the ratio of 1 : 100 in apparent brightness and to a

difference of 5·0 in apparent magnitude. If our assumption were universally true of the stars—that they are all of standard pattern like the houses in a terrace—their distances (in miles) could be found by this principle with the greatest of ease, provided the distance (in miles) of any one star were known; thus one of the great problems of astronomy—the distribution of stars in the stellar universe—could be solved completely.

But the stars do not all conform to the same specifications, so that relative distance is not the only factor which explains the great diversity in the apparent brightness of the stars. The stars vary enormously as regards volume—from the feeble "dwarfs" to the bloated "giants"—and accordingly they vary enormously as regards the area of the surfaces from which their light is radiated into space. The greater the surface area of the star the greater is its brightness. For example, the eye receives twice the amount of light from the moon when full as compared with a half moon; it is simply a question of the area of the illuminated surface visible to us.

Again, the stars vary greatly as regards surface temperature or, more precisely, as regards the intensity of the radiation emitted per square inch of their surfaces, so that, other things being equal, the hotter a star is the brighter it will appear.

There are thus three important factors—it has been our purpose here to do little more than refer briefly to them—namely distance, size and surface brilliancy, which unite to give the great diversity in the apparent brightness of the stars.

Reference has been made already to the early star catalogue of Ptolemy—the forerunner of a great host—in which are given the positions of 1080 stars. The positions of the stars on the celestial sphere are referred to that sphere in very much the same way as that in which points on the earth's surface are described in terms of longitude and latitude. As we have seen, the corresponding names for the star positions are right ascension and declination respectively. A very large proportion of the labours of astronomers for the two and a half centuries following the invention of the telescope has been devoted to the measurement of star-positions with the transit circle or instruments similar in principle, and in many of our modern observatories this department of astronomy, still of fundamental importance, is prosecuted with constant vigour. A

conspicuous feature of any astronomical library is the large number of star-catalogues embodying the results of long and tedious programmes of observation, individual volumes representing in many instances twenty or thirty years of unremitting devotion and incessant toil. It may be inquired: "What is the use of observing and re-observing stars, of straining after greater precision, of extending the survey to fainter and yet fainter stars?" One of the answers is, of course, that the stars form the background against which the movements of the bodies of the solar system are measured; and therefore the star-positions must be known with the accuracy necessary for the proper investigation of the problem concerned. We have seen, for example, how the sun's distance from the earth was deduced from observations of Eros, which were made with reference to the stars themselves. Another most conclusive answer, however, will be given in a succeeding chapter.

It is not our purpose to describe in detail the great star-catalogues which are our heritage from past generations of astronomers; a single reference must suffice. About the middle of the last century a systematic survey of the northern heavens was commenced by Argelander; the results are contained in the great "Bonn Durchmusterung." This catalogue contains the positions of 324,000 stars—the faintest of magnitude 9·5—between the north pole and the parallel of 2° south declination. It was subsequently extended further into the southern sky. From the data of the catalogue, charts were constructed depicting the positions of the stars and indicating their relative brightness. The catalogue and the charts form a great work of reference, a monumental directory of the stars of the northern sky.

The first international conference of astronomers assembled in Paris in 1887 to debate and eventually to plan one of the most ambitious projects of science ever undertaken, namely the photographic survey of the entire heavens. For complete success, the enthusiastic and long-sustained co-operation of some twenty observatories scattered over the five continents was a prime necessity. The magnitude of the work which the project entailed might well have appalled the boldest spirits, but astronomers, as a class, are nothing if not enthusiastic and pioneering; and so, in a spirit of undaunted optimism, the

great survey was inaugurated. The participating observatories employed telescopes of identical pattern—the astrographic telescopes (as they came to be called) of 13 inches aperture and 11¼ feet focal length—and to each observatory was assigned a particular zone of the heavens. The exposures to be given were such as would show measurable images of 14th magnitude stars. The actual work involved in securing photographs of the whole sky was itself a large undertaking, over 10,000 photographs in all being required, but it was insignificant in comparison with the task of measuring the positions and magnitudes of all the stars whose images appeared on the plates. In addition, there was the preparation of catalogues embodying the results and of the reproduction of the photographs in the form of charts. It is not surprising that the resources of certain observatories were unequal to the strain. Despite the defection of one or two observatories and the difficulties experienced by others, the work goes on apace, and had it not been for the interruption caused by the Great War the completion of this stupendous project might have been ere now a *fait accompli*. Several observatories have already finished their share of the work, others are within sight of the end, while one or two, unfortunately, have not made the progress that had been expected of them. According to present estimates this great enterprise should be all but completed by 1933, nearly half a century after its inception.

# CHAPTER IX

## THE PROPER MOTIONS OF THE STARS

IN 1718 the great astronomer Halley made a discovery of momentous importance in stellar astronomy. In a sense it was a simple discovery, for it was the result, not of an advance in instrumental power, nor of the application of new mathematical and physical principles, but rather of acuteness of observation. Having regard to the continual development of astronomical appliances, we can see now that it must inevitably have been made, but this cannot detract in any way from the merit of Halley's discovery. Halley showed, beyond the possibility of doubt, that the positions of the three bright stars, Sirius, Arcturus and Aldebaran, with reference to their stellar neighbours, had altered by a measurable amount since the time of Hipparchus. Let us illustrate by a simple terrestrial analogy. Let us suppose that Hipparchus had been familiar with all the lofty peaks on the earth's surface and had made a rough survey of their positions, leaving to posterity a complete record of his work. Let us suppose that two thousand years later a similar survey was made and the positions re-determined; that a comparison of the two records showed that the positions of three of the highest peaks had apparently, in some mysterious way, been altered by several miles, the remaining peaks remaining to all appearances very much in the same positions. If the hypothetical ancient records are to be trusted, the phenomenon must represent a real change in position of the three peaks with respect to their neighbours. It was by an analogous procedure that Halley made his discovery. Ptolemy's great catalogue of 1080 stars recorded the positions of the brightest stars visible in Mediterranean latitudes; it mapped out, as it were, the stars and constellations. The observations of seventeenth and eighteenth-century astronomers mapped out afresh—naturally with greater precision—the same stars and

constellations. Nearly two thousand years had rolled past and the heavens seemed unchanged and unchanging, and fixity in the unfathomed depths of space appeared to be the chief characteristic of the heavenly host. Halley's discovery revolutionised this conception of the stellar universe. The stars could be described no longer as "fixed" and unaltering. Although no general change in the configuration of the constellations was detected then—with the three exceptions mentioned—might not this be merely because smaller changes and feebler movements were beyond the powers of measurement of contemporary astronomy? Might not all the stars be marching along majestic orbits, the more distant stars so remote that not even a span of 2000 years could suffice to reveal a sensible change in their relative positions in the firmament?

The apparent movements of the stars, such as Halley discovered, are called *proper motions*. As they indicate the changes of position on the celestial sphere, they are measured in terms of angle. Thus the proper motion of Sirius is a little over $1''\cdot3$ per annum; in two thousand years this motion would take Sirius over an angle about one and a third times the angle subtended at the earth by the moon's diameter.

Halley's discovery of the proper motions of the three stars mentioned was quickly followed by similar discoveries relating to many more of the bright stars. It gave a new impetus to stellar astronomy, for it showed the necessity for the observation of star-positions with the greatest possible accuracy. For the next century and a half astronomers applied themselves steadily and whole-heartedly to the task of observing and re-observing the right ascensions and declinations of the stars with the transit circle or similar instruments. The accurate measurement of proper motions requires the lapse of many years between two sets of observations; the fruit was therefore not for the plucking by the earlier astronomers who spent long and arduous hours, night after night, recording the positions of the stars, but by future generations of astronomers who, by making similar observations and by comparing the old and new star-positions, would be enabled to contribute more and more to the store of knowledge regarding stellar movements.

In 1910 the late Professor Lewis Boss published his "Preliminary General Catalogue of 6188 stars," including all those

visible to the naked eye in both the northern and southern hemispheres. This great work is justly regarded as the standard directory of the proper motions of the brightest stars. The great catalogues dating from 1755 onwards were diligently searched; old and new observations of each of the 6188 stars were rigorously compared; the results are the proper motions of this large number of stars determined with an accuracy hitherto unknown—a lasting monument to the diligence, perseverance and skill of five generations of astronomers. One of the most insistent demands of astronomy to-day is for more and yet more measures of the proper motions of fainter and yet fainter stars; it is a call for the exploration of the remoter and yet more remote regions of the stellar universe. We shall see

FIG. 66.

soon how this call can be answered most readily, and we shall record in due course what has already been achieved.

The largest proper motion discovered so far is that of a faint star, the "runaway" star of Barnard, found by him in 1916 to have a proper motion of a little over 10″ per annum. In about 190 years this star will move across the background of the stars through an angle equal to that subtended at the earth by the moon's diameter. A proper motion of half a second of arc per annum, *i.e.* 50″ per century, is exceptional; at the beginning of 1923, 749 stars had been catalogued as having proper motions of 50″ per century or over—a very small proportion of the total number of stars in the sky. The discovery of such exceptionally large proper motions is, of course, by no means at an end, but it is fairly certain that most of these rapidly moving stars have already been gathered by the net of observation.

The effect of proper motion on the configuration of the constellations is illustrated in Figure 66. The left-hand diagram shows the familiar appearance of the "Plough" in the twentieth century. The right-hand diagram shows how it will

appear 50,000 years hence. The proper motions of the seven bright stars of the "Plough" are comparatively small, and the apparent change in the "shape" of the constellation is slow. Such an illustration is representative of the whole sky. The changes in the relative positions of the stars may be slow and gradual; here and there may be a "flying" star; and we abandon perforce the conception of a fixed stellar universe and substitute for it one of ceaseless movement.

Reverting to our definition of proper motion we notice that we can make no deduction regarding the speed of any star (in miles per second) unless we know its distance. For example, after twenty years we observe that a star has moved over a second or two of arc with reference to the general stellar background. Clearly this change in position on the celestial sphere is due to that part of the star's speed which is at right angles to the line of sight, but what this speed actually is the

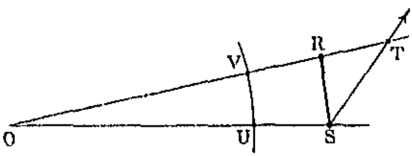



FIG. 67.

proper motion by itself is unable to predict. In Figure 67 let us suppose that a star moves from a point S in space to a point T in one year. We observe it from O, and it appears to move through the angle VOU in a year, which is the measure of its proper motion. If the star had moved from S to R it would have shown the same proper motion. The actual speed at which it moves at right angles to the line of sight, given by its motion between S and R, is called its cross-velocity, and the part of its motion in the line of sight represented by the motion between R and T is called its *radial velocity*, which will be considered more particularly in a subsequent chapter. If we know the distance of the star, that is, the distance OS in Figure 67, a simple calculation gives the cross-velocity (usually expressed in miles per second or kilometres per second). Conversely, if all the stars had the same cross-velocity their proper motions—which it is comparatively easy to measure in practice—would give their distances, which are incomparably

more difficult to measure, provided that we know the distance of any one of them. Thus, on this hypothesis, a star with a proper motion of 5″ per century would be at ten times the distance of one with proper motion of 50″ per century, and so on. The hypothesis, of course, does not hold for individual stars, and consequently stellar distances cannot be measured in this way. The hypothesis, however, is of value in a qualitative way. It is found that stellar velocities cluster mostly round about an average value of 8 or 10 miles per second. It follows that, in general, the nearer a star is to us, the greater the chance that its proper motion is considerable. The converse principle—that a large proper motion probably signifies the comparative proximity of the star—is adopted largely in selecting stars whose distances it is proposed to measure.

The method described in the previous pages for measuring the proper motions of the stars—that is, by comparing old and recent observations of star positions made with the transit circle—is the fundamental method. It suffers, however, from several limitations. In the first place stars fainter than the 9th or 10th magnitude are generally beyond its reach. Secondly, each star has to be observed separately, and usually as many as five observations made on different nights are necessary to determine a star-position with the accuracy required for the precise measure of proper motion. Thirdly, a long interval—about fifty years—must have elapsed between the two sets of observations. It is thus a slow and tedious method.

The precision with which stellar images can be measured on the photographic plate suggests a more powerful method of deriving proper motions which has none of the limitations of the fundamental method, although in the last resort it is dependent on the latter. The principle is best illustrated by the procedure suggested by Kapteyn over twenty years ago. A photograph is made of the region of stars to be investigated; it is stored away undeveloped for, say, ten years, after which it is re-exposed to the same stars. In the second exposure, the setting of the telescope (or of the plate itself) is altered by a minute amount so as to prevent the star images of the second exposure from falling exactly over the latent images of the first. After the second exposure, the plate is developed in the

usual way, and it is then found that each star is represented by two images close together, one recording the early exposure and the other the later one. Figure 68 illustrates the method. The black dots represent the stellar images made, say, in 1910; the open circles those made in 1920 (on the negative, of course, both the 1910 and 1920 images are black dots, but for purposes of clearness in exposition we shall represent the 1920 images in the manner indicated). If the stars were truly motionless, the configuration of the star images on the plate would be the same in 1920 as in 1910, and consequently—if the proper instrumental precautions have been taken—each pair of images, such as A or B or C, would be identical, as regards separation and direction, with every other pair. If a star, however, has an appreciable proper motion, it is at once revealed in the photograph. Thus in Figure 68 the 1920 image of the star D is at the point Z; if it had no motion at all the image would have been at Y, the direction and distance of Y from X (the 1910 image) being the same as for the motionless stars A or B or C. The star has evidently altered its position on the celestial sphere, in the interval, through an *angle* and in a direction represented by YZ on the photographic plate. Distances between images on the photographic plate can be measured very accurately. With the Cambridge measuring instrument, distances can be measured to a fifty-thousandth part of an inch. The distance on the plate between the 1910 images of two stars A and B is, let us say, one inch; if the angle between the directions of the two stars in the sky is known, the relation between the angular separation of the two stars and the measured distance on the plate is easily established. For example, for plates taken with the Sheepshanks Telescope of the Cambridge Observatory, 1″ of arc is represented by about $\frac{1}{800}$ of an inch. The process of measurement is illustrated in Figure 68 for the pair of images of the star A.

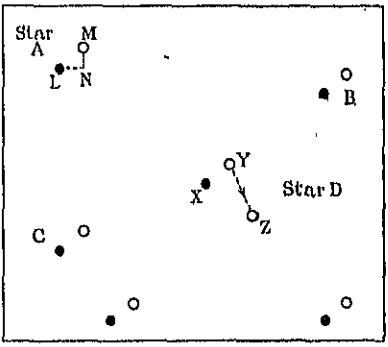


FIG. 68.

Perpendicular scales with which the measuring machine is provided enable the horizontal distance LN (parallel to the celestial equator) between the centres of the 1910 and 1920 images to be measured, and afterwards the vertical distance NM (in declination). This procedure is followed for all the pairs of images. For the star D, with the large proper motion, the horizontal and vertical distances between X and Z are obtained in the manner indicated; the horizontal and vertical distances between X and Y are inferred from the measures made on such stars as A or B or C, and consequently the horizontal and vertical distances between Y and Z are derived. These latter distances, converted into angular measure, give finally the proper motion of the star—expressed as so many seconds of arc per year or per century—in right ascension and in declination respectively.

There is an obvious objection to this method, not as regards principle, but as regards practical application. The accuracy of proper motions depends largely on the interval between two sets of observations or two sets of photographic exposures—the longer the interval the greater is the accuracy. A partially exposed photographic plate cannot be stored away undeveloped indefinitely without suffering some deterioration as regards the film and the latent images of the first exposure. Also it is uncertain until long afterwards whether the first exposure has been successful or not, for the images must be circular and well-focussed. A modification of the method, without the disadvantages referred to, was adopted at Cambridge in 1921. This observatory, in common with others, has a large and valuable stock of plates of excellent quality taken, for quite different purposes, in 1900 and succeeding years, and developed immediately after exposure. If a photograph of a part of the sky, for which there are early plates, is taken after an interval of about twenty years in such a way that the plate is placed with its film side away from the object glass of the telescope, the star light consequently passing through the clear glass of the plate before falling on the under side of the photographic film, then such a plate can be superimposed over an old plate, film to film, with corresponding images close together as in Figure 68. The measurement of the combined plates proceeds in the manner described for the single and doubly exposed plate. In practice,

the calculation of the proper motions from the measures is not quite so simple as outlined here; for example, it is practically impossible to superimpose one plate over another with the accuracy suggested by Figure 68. This and other deviations from the idealistic conditions assumed for the purpose of simple exposition are easily taken account of. It is advantageous, as well as economical, to make several exposures on each plate so that on a combined pair of plates—one photographed directly and the other through the glass—each star is represented by three or four pairs of images.

Photographic proper motions are not "absolute" proper motions in the sense that transit circle proper motions are. The latter give a true account of the change in position of the star on the celestial sphere. For all we know, every star in the photographs (Figure 68) with the exception of D may have identical proper motions which would be masked as such merely because of the method by which one plate is arbitrarily superimposed on the other. The consequence is that the proper motion of D deduced from the measures would differ from its true value by the amount of the supposed common proper motions of all the other stars. If, however, there are in the region photographed one or more stars whose proper motions have been deduced from transit circle observations the differences between these values and the values obtained from the photographic plates give the correction to be applied to all photographic proper motions. This method of converting the relative proper motions of the photographs into "absolute" proper motions is not always possible owing to lack of stars with the necessary information. Another method is adopted in practice, but it is unnecessary to describe it here.

The discovery of proper motions of the stars naturally led in due course to the suggestion that the sun, itself a star, may be in motion relatively to its stellar neighbours. Further, it was asked: "May not the observed proper motions be simply and wholly the reflex effect of the solar motion?" The reader is familiar with the following simple analogy. If one looks out of a train travelling along a straight stretch of railway, objects near the line appear at first almost straight ahead, but as the train approaches they open out in direction, are soon abreast, and in a few minutes are in the direction of the rear

of the train; while distant objects show little change in direction. To the observer in the train the apparent motion of the objects is *away* from the direction in which the train is heading and towards the opposite direction. If the sun has a motion in space the resulting apparent motions of the stars would similarly exhibit a general tendency of movement *away* from a definite direction on the celestial sphere, the nearest stars showing, in general, the greatest proper motion and the most distant stars hardly any. Figure 69 illustrates the principle. The sun moves, we shall suppose, from S to T in one hundred years. In 1800 the direction of a near star is along SU, and in 1900 along TU; the change in direction in one hundred years is the angle TUS, which is consequently observed as proper motion.

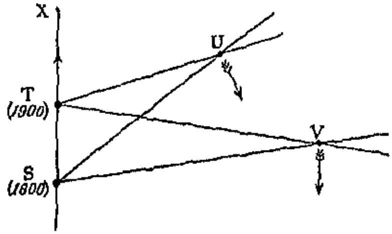


FIG. 69.

For a star X, in the direction in which the sun is moving, there is, of course, no change in its direction as viewed from the sun.

From the diagram the following principles are deduced: (i) the effect of the solar motion is to cause the stars to appear to move away from the direction in which the sun is moving—on the celestial sphere the point to which the solar motion is directed is called the *solar apex*—and to appear to move towards the opposite direction (the solar antapex); (ii) stars in or very near the direction of the solar apex or antapex are unaffected by the solar motion, and for stars at the same distance from the sun the resulting proper motion is greatest for those in directions perpendicular to the direction of the solar motion; (iii) for two stars in nearly the same direction the apparent proper motion is greater for the nearer star. The proper motion of a star resulting from the solar motion is called its parallactic motion. It should be added that Figure 69 makes no pretension as to accurate representation of distances; if U is our nearest stellar neighbour, the distance SU should have been made nearly 700 times the distance ST.

Sir William Herschel first applied this principle in 1783. With a meagre amount of proper motion data he succeeded in

howing that the general tendency of the observed stellar movements was away from a certain point of the celestial sphere —the solar apex—situated in the constellation of Hercules and not far from the bright star Vega, a result confirmed by modern and more exhaustive researches.

The problem of determining the solar apex is complicated by the individual motions of the stars themselves. In Figure 69 we have pictured the stars such as U and V like ships at anchor, only one ship, S, that in which we are passengers, being in motion. But the restriction must be withdrawn. It thus follows that the meaning of the solar motion becomes more difficult to define, for our only reference marks are the stars themselves, and they have their own individual motions. If we suppose that there are one hundred stars in the neighbourhood of U in Figure 69, and that, further, their individual space motions are haphazard as regards both magnitude and direction, then this group of one hundred stars may be regarded, as a group, "at rest." Now the solar motion gives the group a fictitious or apparent motion. On the assumptions made, the average of the observed proper motions corresponds to the effect produced by the solar motion; in other words, the average of the observed proper motions is the parallactic motion of the group. Several such groups fix the direction in which the sun is moving relatively to the groups each regarded as "at rest." When the proper motions of several thousand stars scattered over the sky are combined in this way, the solar motion is defined strictly with reference to these stars as a whole. At present, we are ignorant of the proper motions of all but the nearest stars; when our inquiries embrace the most distant regions of the stellar universe the solar motion can then be defined in relation to the whole body of stars regarded as a single immense group.

Even then we are no nearer the conception of absolute solar motion, for extra-stellar space is unprovided with anything in the shape of fixed landmarks. A ship's engineer can tell from a dial recording the number of revolutions of the propellers per minute the ship's speed through the water; he finds it to be 16 knots. If the ship is proceeding down a river the navigator on the bridge can also calculate the ship's speed from the observation of fixed objects and their positions

on his charts; he finds the speed to be 20 knots with reference to the land. Both the engineer and navigator are, of course, correct; but the latter has the greater amount of information, for he also knows the ship's speed according to the performance of the engines, and he concludes that the river is flowing at 4 knots. The astronomer is in the position of the engineer; space is not provided with charted landmarks and therefore the absolute motion of the sun or of the stars is an abstraction. The solar motion—let it be emphasised—is motion with reference to a particular group of stars regarded, as a group, "at rest"; and, moreover, this group, at present, represents only that small part of the stellar universe in the immediate neighbourhood of the sun.

Proper motions allow us only to determine the direction in which the sun is moving with reference to this group of stars. Numerous investigators agree in locating the position of the solar apex on the celestial sphere near the point indicated by right ascension $18^h$, declination 30° N. (this is about 11° from Vega). It will be shown in a later chapter how the speed of the sun is found; it will be sufficient here to state the result, viz. 20 kilometres per second or 12 miles per second.

The stars are not all independent entities, but are frequently bound together by ties of close association in space and of common characteristics. We shall give three illustrations of families of stars whose affinity is suggested or corroborated by means of the observed proper motions.

The Pleiades, familiar to observers in the northern hemisphere, form a compact group of stars in the sky, of which six or seven are easily visible to the naked eye; with the telescope the number is greatly augmented. Do these stars form actually a compact group in space? Or is it only by a curious freak of chance that they appear to us to be close together in the sky? The measured proper motions supply a criterion whereby it is possible to give a conclusive answer. It is found that there is a pronounced community of proper motions which could only be expected if the stars are members of a definitely localised group. Other tests corroborate this conclusion. The Pleiades thus form a definite clustering of stars moving together in space, like a flight of birds over the wide expanse of the ocean.

The star Capella—the most brilliant star in our northern

sky—has a large and well-determined proper motion. Close to it in the sky, about 12 minutes of arc away, is a faint star of the 10th magnitude, which has practically the same large proper motion. There is little doubt that the glorious orb (itself a double star, but invisible as such in the telescope) is accompanied in its voyage through space by a feeble and unpretentious member of the stellar universe—a giant and a dwarf in close association. Figure 70 shows Capella and its faint companion; the arrows indicate the direction in which the two stars are moving over the sky. The other stars shown have very small proper motions.

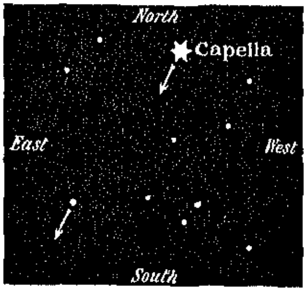



FIG. 70.

The southern sky provides a system similar in many ways to that of Capella. The second brightest star in southern declinations is α Centauri, itself a double star easily seen as such in a small telescope. It is accompanied by a faint star of the 11th magnitude, about 2° away, which has the distinction of being our nearest known stellar neighbour. The measured proper motions of α Centauri and its faint attendant—Proxima Centauri, as it is aptly named—are nearly identical, and as they are conspicuously large the close relationship between the stars is beyond doubt. Corroboration, if need there be, is afforded by the measures of the distances of the stars, Proxima being just a trifle nearer than its more splendid companion. Figure 71 gives a sketch of the system.

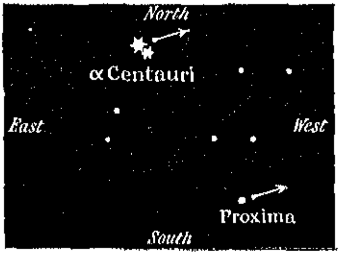



FIG. 71.

We shall conclude this chapter by describing briefly an interesting discovery in which proper motion played a leading part. In practice, proper motion implies a uniform rate of change of position on the celestial sphere; that is, it implies that both the right ascension and declination are, in general, altering at a uniform but minute rate, due allowance being

made for precession and nutation. Or expressing it somewhat differently, if we know the observed right ascension and declination of a star with proper motion at intervals of ten years, for example, and if we plot these positions on a chart of adequate scale, the series of positions will lie on a straight line. In Figure 72, the stars A, B and C are supposed to have little or no proper motion, so that their positions remain practically unchanged throughout an interval of, say, fifty years. The star D, however—we suppose—has a large proper motion, so that its positions corresponding to successive observations lie on a straight line, as represented in the figure.

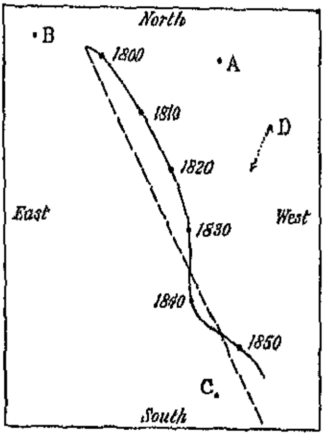


Fig. 72.

In 1844 the celebrated German astronomer Bessel announced that the proper motions of the bright stars Sirius and Procyon did not behave according to this principle. Observations extending over a considerable interval of time showed that their right ascensions and declinations did not alter at a uniform rate. In Figure 72, the curved line represents on an exaggerated scale the manner in which the position of Sirius on the celestial sphere, with reference to the three practically fixed background stars A, B and C, altered owing to its variable proper motion. Bessel found from a long series of observations that the changes in the proper motion of the two stars were cyclical in character, and that in particular the period of such changes for Sirius was about fifty years. He concluded that the observed irregularities were due to invisible companions. Sir William Herschel had shown earlier that of the many double stars which he had observed at long intervals, many exhibited unmistakable signs of orbital motion, so that it was assumed that the law of gravitation operated in the distant stellar regions as well as in the solar system. According to simple dynamical principles the motion of a double star system (a binary star so called) in space is very much like that of a pair of waltzers in a ballroom.

The pair, as a pair, proceed for a certain time in a straight line, but the actual motion of one of the partners over the floor is made up of (*a*) the general progression in a straight line, and (*b*) a whirling or orbital motion. For one component of a binary star, the motion in space consists of (*a*) the general motion of the system in a straight line and (*b*) the orbital motion about the centre of gravity of the pair. Consequently, the observed proper motion of the bright component is not uniform but cyclical, and the period within which the changes recur is merely the period of revolution of the bright star about the centre of gravity of the system.

Bessel's deduction that Sirius and Procyon are not really single stars, but are the principal partners of binary systems, was corroborated fully by direct telescopic observation; in 1862 the feebly luminous "companion" of Sirius was first seen in the telescope, and in 1896 the "companion" of Procyon. We shall have further occasion to discuss the companion of Sirius, one of the most remarkable stars in the heavens.

Bessel is justly described as the founder of the "Astronomy of the Invisible." He was one of the first to suggest that the minute erratic movements of Uranus were caused by the attractions of an unknown planet (Neptune), and we have just seen how he sensed, surely and unmistakably, the existence of stars which the telescopes of his time were powerless to reveal.

# CHAPTER X

## THE STAR STREAMS

UP to 1904 the question, "Do stars move about in space according to more or less definite laws, or are their space motions rather haphazard in character?" had not been seriously considered by astronomers; certainly until that year there was no conclusive evidence offered in support of either alternative. However, it was generally assumed, as a convenient hypothesis, that stellar movements were in fact haphazard and that the universe of stars was a kind of chaos in which no law or order had been detected. The picture of the stellar universe, in the minds of astronomers before 1904, resembled in many ways the picture one would have, from a stationary balloon, of a crowd of people walking aimlessly about within a great open park at all speeds, say, up to 4 miles per hour. People would be observed walking about haphazardly in all directions, and if the observer in the balloon were provided with adequate facilities for counting the number of people proceeding in a particular direction, he would find that this number would be practically constant, whatever the direction considered. If he were asked to demonstrate his results diagrammatically, he would probably proceed as follows (Figure 73). From a point O he would draw the directions North, East, etc., and for each direction, such as OA, he would mark off OP, so many inches, to represent the number of people walking in this direction. Whatever the direction, the number of people moving in that direction is the same as for any other direction,

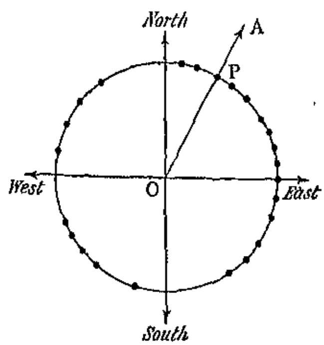



FIG. 73.

and so the diagram would consist of a series of dots all at the same distance from O and therefore lying on a circle whose centre is at O. The circle drawn in this way is called a *frequency curve*. Now let us complicate this illustration by supposing that the balloon is loosed from its moorings and that it drifts southwards at 2 miles per hour. A person walking southwards at 2 miles per hour would now appear to be stationary relatively to the balloon; a person walking at 1 mile per hour southwards would appear, to the observer, to be moving northwards at 1 mile per hour; a person moving eastwards would appear to be moving in a north-easterly direction; and so on. To the observer, then, there would be many more people who seem to be moving northward than southward, moving north-easterly than south-easterly, and so on. His frequency curve would now be something like Figure 74, in which, for example, the number of people appearing to move in the direction OA is represented by the distance OP, which is very much greater than the distance OQ, representing the number of people appearing to move in the direction OB.

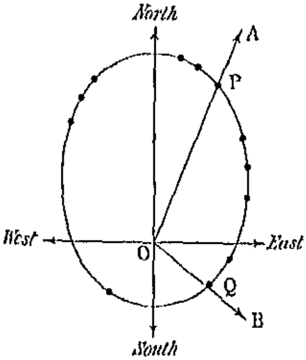


FIG. 74.

Let us now confine our attention to a small part of the sky. There we see, or photograph, a large number of stars at varying distances from us. Their movements in space give rise to the apparent motions on the celestial sphere which we call their proper motions. If we assume that their space motions are entirely haphazard, then the observed proper motions also appear to be haphazard, and by counting the number of proper motions in each direction we should derive a frequency curve like Figure 73. But this is not the whole truth, for the sun (or the solar system) is moving towards the solar apex with a speed of 12 miles per second, and therefore our group of stars will appear to us to move as a whole towards the solar antapex. This will be in a particular direction in the sky, depending on the position of our group of stars on the celestial sphere. Counts of proper motions in different directions would then result

in a frequency curve such as Figure 75, similar in general to Figure 74 of our illustration but pointing in a particular direction, namely, that of the solar antapex. The feature of the curve is that the great majority of the stars appear to be moving in or near the direction of the solar antapex and comparatively few in or near the opposite direction; expressing it somewhat differently, we say that the general tendency of the proper motions is in the direction of the antapex. Such a distribution of proper motions is called a *drift*.

This principle, which is essentially contained in Figure 75, can be readily applied to test the validity of the hypothesis that the stellar movements in space are entirely haphazard, for if the frequency curve for every restricted region of the sky possesses the general characteristics of Figure 75, we must naturally conclude that the hypothesis is extremely probable if not certainly true.

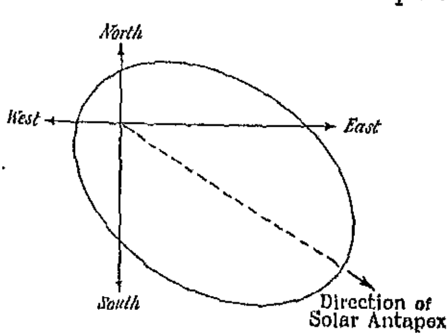



Fig. 75.

In 1904 Professor J. C. Kapteyn announced his discovery of star-streaming, a discovery which effectively disposed of the conception of the stellar universe as a chaos of stars, each with its own independent motion in space. The material at his disposal consisted of the proper motions, derived from transit circle observations, of the brighter stars in the sky.

Confining his attention to one small part of the sky at a time, Kapteyn showed in effect that the counts of proper motion in different directions did not yield a simple curve similar in type to Figure 75, but a more complicated curve of the character shown in Figure 76. Such a curve cannot be interpreted, on any conceivable grounds, as a single drift curve of the type shown in Figure 75; but Kapteyn was quick to perceive that it could be interpreted as a composite curve, consisting of two drifts, one pointing in the direction OA and the other in the direction OB. The constituent drift curves

are shown dotted in Figure 76. It is well to remember that the observed curve (in full line) gives the number of observed proper motions in the various directions. Thus the length of the line ON is proportional to the number of stars with observed proper motions in the direction OK. This number is made up of (*a*) the number, proportional to the length of OM, of stars moving in the direction OK and belonging to the drift which points along OA and (*b*) the number, proportional to the length of OL, of stars moving in the direction OK and belonging to the drift which points along OB. Different parts of the sky yielded frequency curves of the proper motions which could generally be split up into two single drift curves. Generally,

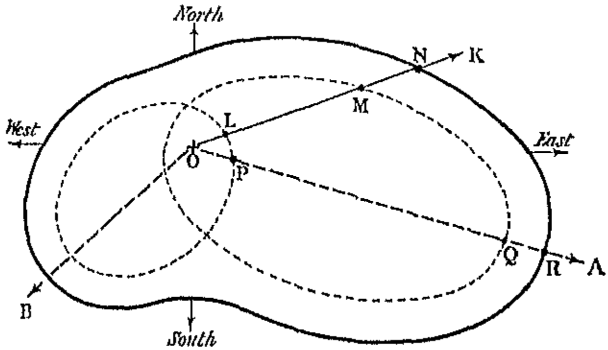



FIG. 76.

too, one drift was more prominent than the other, as in Figure 76 where the drift pointing in the direction OA is clearly more prominent than the drift pointing in the direction OB. Let us consider, for a moment, only the "prominent" drifts. It was found by Kapteyn that the directions in which they pointed varied according to the part of the sky that was under consideration, but that these different directions were not haphazard. If devout Mohammedans turn their faces accurately towards Mecca at the time of evening prayer, the directions in which they face will vary according to their positions on the globe; Mohammedans in India will face, roughly, west; in Asia Minor, south; in Australia, north-west, and so on; but the directions will all converge to Mecca. So it is with the directions of the drifts as revealed in different parts of the sky. Kapteyn found

that the directions of the prominent drifts converged fairly accurately to a certain point on the celestial sphere, called the "apex of Drift I." In the same way, the directions in which the less prominent drift pointed converged to a different point on the celestial sphere, called the "apex of Drift II." What is the interpretation of this phenomenon?

If the stars with which we are dealing were moving about in space with quite haphazard motions, we should obtain, as we have seen already, from the observed proper motions of stars within a restricted part of the sky a single drift curve, for on account of the solar motion the observed proper motion of each star consists of the proper motion resulting from its individual random motion together with the parallactic motion. Or expressed somewhat differently, the group of stars, considered as a swarm, would appear to be moving, as a swarm, relatively to the sun in the direction opposite to that of the solar motion, so that the observed proper motions would form a single drift pointing, in the sky, in the direction of the solar antapex. Now the observed frequency curve of the proper motions consists of two distinct drifts and one interpretation of the phenomenon is that there are two swarms of stars moving in two distinct directions relatively to the sun. We have seen that if we envisage the sky as a whole, the prominent drifts in the different parts of the sky are directed towards a definite point on the celestial sphere; this must mean that all the stars in the sky which contribute to the prominent drifts are moving, as a whole, in a definite direction relatively to the sun, defined by the direction of the apex of Drift I. Similarly for Drift II. Now, the observed proper motions and also the two drifts contain the effect of the solar motion. If this effect is removed, the general body of the stars is then seen as if it consists of two intermingled stellar swarms moving in opposite directions in space. These are the two star streams of Kapteyn. Let us suppose that the reader is looking down on a busy thoroughfare running east and west. He sees people walking eastwards, and people walking westwards; some are crossing from one side to the other at all angles. His general conclusion from his observations of all the varied directions in which the people are moving is that the traffic consists of two intermingled streams, one moving as a whole eastwards and the other as a whole westwards. It is

somewhat in this way that we can picture the two intermingled swarms of stars, the two star streams. It is not to be understood that all the stars of one stream are moving in the same direction and all the stars of the other stream are moving in the opposite direction; the picture is rather of one swarm with a general tendency of motion in one favoured direction and of another swarm with a general tendency of motion in the opposite direction. The universe of stars is a flattened system with much greater extensions in the plane of the Milky Way than at right angles to this plane. It is significant, then, that the directions of motion of the two star streams lie in this fundamental plane.

All researches dealing with the stellar motions since the time of Kapteyn's discovery have confirmed the phenomenon of star streaming. The numerous and highly accurate proper motions of Boss's Catalogue provided the material with which Professor A. S. Eddington was enabled, in 1910, to calculate with great precision the characteristics of the two star streams; in particular, he found that, averaging over the whole sky, the numbers of stars in Stream I and Stream II were in the ratio of 3 to 2; also, the position of the solar apex which emerged from his investigation, agreed very closely with the results of the older methods.

The stars in Boss's Catalogue are the naked-eye stars, presumably, in general, the nearest stars. Does the phenomenon of star-streaming extend to more distant regions of the stellar universe? Is it, for example, a feature of stars as faint as the twelfth magnitude? The proper motions of faint stars, obtained from the measurement of photographic plates, reveal the presence of star streams with almost the same characteristics as those found for the near and bright stars—with this difference, that the well-marked numerical superiority of the bright stars of Stream I over Stream II gives place to what is virtually a numerical equality.

Figure 77 shows the effect of star-streaming in a particular part of the sky; the proper motions of the stars were recently obtained from photographs taken at Cambridge Observatory. In all, there are 284 stars, many of them as faint as the eleventh magnitude. The full line curve shows the observed distribution of the proper motions in the various directions. The frequency

curve undoubtedly shows two drifts—Drift I pointing in the direction OA and Drift II in the direction OB. By a process into the details of which we need not enter it is evidently possible to choose two theoretical drift curves, one pointing along OA and the other along OB, which will combine to give a frequency curve resembling the actual frequency curve deduced from observation. This combined curve—shown in a broken line—agrees very well with the observed frequency curve, and minor discrepancies are to be attributed to the inevitable errors

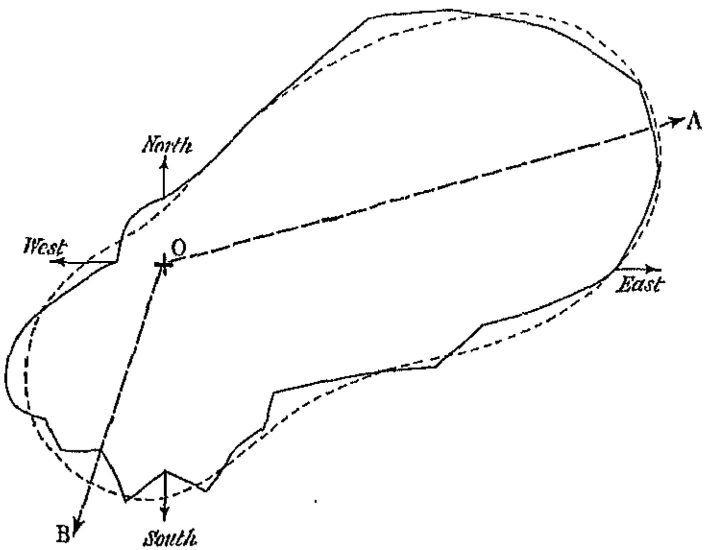



FIG. 77.

involved in the measurement of the generally small proper motions of the faint stars. Figure 77 is typical of what is observed in any other part of the sky.

What is the significance of this fact of star-streaming in the internal economy of the stellar universe? Does the interpretation of our observations really mean that there are two intermingled groups of stars, or is star-streaming the visible evidence of some dynamical characteristics of the stellar universe as a whole, whose secrets we have only dimly glimpsed? We must remember that our exploration of the stellar universe—as regards the observation of proper motions

—has not gone very far. It is as if an Englishman had explored with tolerable completeness his own country but remained in perfect ignorance of all the lands beyond his own encircling sea. Star-streaming remains a puzzling phenomenon ; tentative explanations have indeed been offered, but it would appear that its complete elucidation is a task for future astronomers.

# CHAPTER XI

## THE DISTANCES OF THE STARS

THE Copernican theory of the solar system had an immediate application to the problem of stellar distances; in fact, the fundamental method of measuring the distances of the stars in use in all the great observatories of the world to-day was first suggested by Galileo in his famous "Dialogue on the two chief systems." The principle of the method is extremely simple. In the course of a year, the earth revolves around the

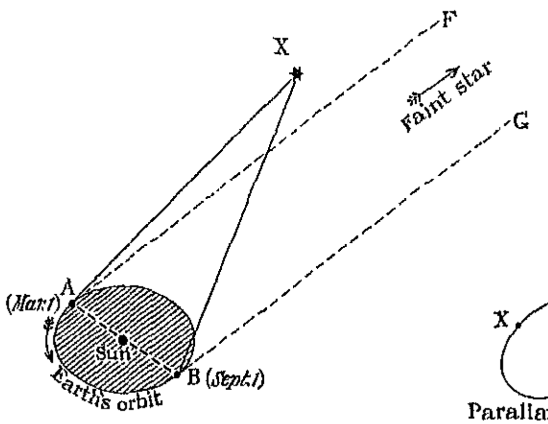



FIG. 78a.


FIG. 78b.

sun in a mighty orbit (which we shall regard simply as a circle of radius about 93 millions of miles); consequently, we view the heavenly bodies, from day to day, from different points of space. Let us consider two stars seen in the telescope, one a bright star and the other a faint star; the former we shall presume to be comparatively near the sun and the latter at an exceedingly remote distance. In Figure 78*a* let the curve ACB represent the earth's orbit round the sun (S), and suppose that the earth is at the point A in its orbit on March 1 and six months later

at the point B. Let X denote the position in space of the near star. The faint and very distant star we shall suppose to be somewhere on the line AF at a great distance from A. Given suitable instrumental equipment, it is possible to measure with great accuracy the angle between the two stars in the field of view of the telescope. On March 1, then, the angle between the stars is measured—in our diagram, this is the angle XAF. Six months later, the angle is again measured. In the interval, the earth's position has changed from A to B and the angle measured on September 1 is now XBG in the diagram, where the line BG is drawn parallel to AF, for the faint star is presumed to be so far off that its direction remains practically the same whether it is viewed from A or from B. Taking the simplest possible case, we shall suppose that the direction of the star X from the sun S is at right angles to the orbital diameter AB and that the faint star is in the plane XAB. In this instance, the difference between the observed angles XBG and XAF is the angle AXB. Now we know the base line AB to be 186 millions of miles and we have measured the angle AXB; from all the data of the problem, a simple calculation leads to the distance SX, the distance of the star from the sun. The angle subtended at the star by the radius of the earth's orbit is called the *parallax* of the star; in Figure 78*a*, it is the angle SXA or half the measured angle AXB. The nearer the star is to us, the greater is its parallax, and vice-versa. Parallaxes measured according to the principles just described are known as *trigonometrical parallaxes.*

If a series of observations is made throughout the year, it is clear that the direction of the bright star will appear to alter continuously with respect to the direction of the faint star. Projected on the sky, the curve which X appears to describe with reference to the faint star F is an ellipse, called the parallax ellipse (Figure 78*b*).

These principles were early appreciated by astronomers, but when attempts were made to observe the apparent displacements illustrated in Figure 78*b*, they resulted in complete failure. Either the Copernican theory was wrong—in particular, the earth did not revolve around the sun—or stellar distances were so stupendous that the apparent annual displacements of the near stars were too minute to be detected by telescopes then in

use. But all the other known astronomical phenomena harmonised completely with the Copernican view; thus there was no alternative but to accept the inference that the stars are at incredibly great distances from the solar system. Clearly, the successful measurement of stellar distances depended on the sufficient development of instrumental power and efficiency.

Let us see what the problem demanded of the practical astronomer. The nearest star, it is now known, is about a quarter of a million times 93 millions of miles away from the sun; its parallax is three-quarters of a second of arc—this is the minute angle subtended at the star by the radius of the earth's orbit. It is the angle subtended by the diameter of a halfpenny (diameter 1 inch) at a distance of 4¼ miles. In terms of light-time (the velocity of light is 186,000 miles per second) the nearest star is so far away that its light, travelling at this stupendous speed, takes 4¼ years to traverse the intervening space. Clearly, instruments of extraordinary precision are necessary to measure angles that are but fractions of a second of arc, and it is not surprising that it was not for 2¼ centuries after the invention of the telescope that the supreme effort of stellar astronomy was crowned with success.

At the end of the first quarter of the nineteenth century, astronomers had evolved the general principles to be applied to the selection of stars which might be expected, on these principles, to be nearest to us and therefore most likely to give positive results when the arduous work of observation was commenced. The first principle related to the apparent magnitudes of the stars. If all stars are alike in intrinsic luminosity, their apparent brightnesses are simply the effect of distance; as we have seen in Chapter VIII, if a first magnitude star were supposed removed to 10 times its present distance, it would then appear as a sixth magnitude star, and accordingly its parallax would be one-tenth of its present parallax. It was natural then to expect that stars of the first and second magnitudes would be found to be amongst our nearest neighbours. The hypothesis underlying this principle we now know to be untenable and to-day we should express the principle as follows:—That of all the first and second magnitude stars, it might reasonably be expected that a small proportion at least would be found to have large parallaxes.

If the original hypothesis is uniformly true, the distances of all stars could be easily derived provided that the relative apparent brightness of the sun and a first magnitude star, for example, could be measured. Actually, by a comparison of the brightness of the sun and Arcturus, Steinheil was led to the result that if the sun were removed to a distance equal to 3¼ million times its present distance from the earth, it would appear of the same brightness as Arcturus; and if the sun and Arcturus are assumed to be similar stars the parallax of Arcturus is therefore found to be $0''\cdot06$. However the practical problem of measuring the relative brightness of the sun and a star is one of great difficulty. The known parallax of Arcturus is $0''\cdot08$ from modern measurements, so the comparative success of Steinheil's deduction must be accounted, in great measure, a lucky accident.

The second principle relates to proper motion as a criterion of proximity. If a star has a proper motion of $1''$ per annum, then at half its present distance, the proper motion would be $2''$ per annum, if its space velocity remained unaltered. A proper motion of $1''$ per annum is an exceptionally large proper motion, and stars with this characteristic may be confidently presumed to be near and therefore to have a large parallax.

The third principle concerns binary stars. Allusion has been made in a previous chapter (page 168) to Sir William Herschel's discovery of orbital motion in several double star systems. His original exploration of the heavens for double stars was undertaken with a view to the discovery of suitable systems of the character represented in Figure *78a* which could be carefully observed in the hope of the detection of parallax. His subsequent discovery that many of these double star systems were in truth physically connected systems led him away from his early parallax plans. Now, we have seen that in the solar system the nearer a planet is to the sun, the shorter is its period of orbital revolution, and we have also seen that the orbital period and distance from the sun are governed by a definite relation involving the sum of the masses of sun and planet (the amended third law of Kepler). Now the observations of a binary star yield two results; one, the angle of separation between the components and the second, the period of revolution of one component about the other. If the masses

of binary star systems are all much alike, then the shorter the orbital period, the nearer the components will be to each other; and the larger the angle of separation, the nearer the system will be to the sun. The third criterion of proximity to the sun is then, briefly, short orbital period combined with large angle of separation of the components. We shall see in due course that there is surprisingly little variation in stellar masses, and so this principle is an extremely reliable one.

The plan of attack on the measurement of stellar distances consisted first of all in making a list of stars which conformed to each of the three principles. There were, firstly, the bright stars of the first and second magnitude. Secondly, there were stars like Sirius, Procyon, 61 Cygni, Vega and $\alpha$ Centauri with remarkably large proper motions. Thirdly, there were binary stars with undeniable indications of rapid orbital motion such as $\alpha$ Centauri, 61 Cygni, p Ophiuchi, etc. If one particular star was included in two or in all three groups, the probability of its nearness to us was very greatly strengthened.

Bessel selected 61 Cygni (a fifth magnitude star) for observation. In his time, it was known as the "flying star," its proper motion being $5''\cdot 2$ per annum. It is also a binary star with large angular separation and fairly rapid orbital motion. According to both the second and third criteria, there was exceptionally strong evidence for believing it one of our nearest stellar neighbours.

The elder Struve selected the first magnitude star Vega with the large but not exceptional proper motion of one-third of a second of arc per annum.

Henderson, H.M. Astronomer at the Cape, selected the first magnitude star $\alpha$ Centauri—the third brightest star in the heavens—with the extremely large proper motion of $3''\cdot 7$ per annum, and a binary star with rapid orbital motion. This star therefore satisfied all three criteria, and was undoubtedly the most promising subject for the measurement of stellar distance.

Almost simultaneously, the hitherto closed barriers of space were broken down. Towards the close of 1838, Bessel announced that he had succeeded in measuring the parallax of 61 Cygni: his result was $0''\cdot 31$, within 3 per cent. of the best modern measures, truly a remarkable achievement. As Miss Clerke, the distinguished historian of astronomy, has written, Bessel's

success is "memorable as the first *published* instance of the fathom line, so industriously thrown out into celestial space, having really and indubitably touched bottom."

Henderson was appointed in 1831 to his office at the Cape, but owing to ill-health he returned to Scotland in 1833. During his brief stay at the Cape, $\alpha$ Centauri was observed assiduously. His observations were not reduced for some time, but early in 1839 he announced the results of his labours, namely, a parallax of $1''$, the accepted present-day value being $0''\cdot75$. According to Sir John Herschel, "the distinct and entire credit of the *first* discovery of the parallax of a fixed star will rest indisputably with Mr Henderson."

In 1840 Struve announced that the parallax of Vega was $0''\cdot25$, the best modern measures leading to a value of $0''\cdot12$. The triple success was remarkable also for the fact that the three astronomers employed totally different types of telescopes. Bessel's instrument was the famous heliometer, a refracting telescope with a divided object glass, the first telescope to be driven by clock-work. In this type of instrument each half of the object glass forms a separate image of a star, so that in the field of view each star has two images (*a*) and (*b*). By sliding one-half of the object glass along the other half, the image (*a*) of one star can be superimposed over the image (*b*) of another star. From readings of standardised scales giving the amount of separation of the two halves of the object glass, the angle between the stars can be accurately measured. Bessel utilised two faint stars by means of which the displacements due to parallax were measured. Struve employed an ordinary refracting telescope fitted, at the eye-piece end, with a micrometer actuating a movable spider line, which could thus be placed over the bright star and then over a faint comparison star, the difference in the micrometer readings providing the measure of the angle between the stars. Both Bessel's and Struve's methods of measuring stellar parallax were thus according to the principles illustrated in Figure 78*a*. Henderson, on the other hand, dispensed with the intermediary faint star and observed the right ascension and declination of $\alpha$ Centauri with the transit circle, thus obtaining directly the small fluctuations, due to parallax, of the star's position on the celestial sphere.

Such, in brief outline, is the history of one of the most

remarkable achievements of human endeavour, the first soundings of celestial space. In February 1841 Sir John Herschel, addressing the members of the Royal Astronomical Society on the occasion of the award of the Society's Gold Medal to Bessel, uttered these words: "I congratulate you and myself that we have lived to see the great and hitherto impassable barrier to our excursions into the sidereal universe—that barrier against which we have chafed so long and so vainly—almost simultaneously overleaped at three different points. It is the greatest and most glorious triumph which practical astronomy has ever witnessed. Perhaps I ought not to speak so strongly—perhaps I should hold some reserve in favour of the bare possibility that it may all be an illusion, and that further researches, as they have repeatedly before, so may now fail to substantiate this noble result. But I confess myself unequal to such prudence under such excitement. Let us rather accept the joyful omens of the time and trust that, as the barrier has begun to yield, it will speedily be prostrated. Such results are among the fairest flowers of civilisation."

The efforts of the next two generations of astronomers in the domain of stellar parallax met with only moderate success. Sir David Gill at the Cape and Elkin at Yale were the chief workers. The barriers had indeed begun to yield, but more powerful weapons and more efficient methods were necessary for a deeper and more sustained advance into celestial territory. It is noteworthy that Canopus—the second brightest star in the sky, with the very small proper motion of just over 2″ per century—was found by Gill to have a very minute parallax, smaller than the unavoidable errors of observation; its distance must therefore be exceedingly great.

The introduction of photography into the realm of precise astronomy gave fresh encouragement to workers—among whom Pritchard of Oxford was a notable pioneer—in this most difficult department of practical astronomy. The principles of the photographic method are essentially the same as in the visual method illustrated in Figure *78a*. The parallax displacements of the near star can be measured, with reference to several faint stars, with an accuracy far surpassing that attainable in the visual observations. Also by means of longer exposures, very much fainter stars are made available for the

necessary comparisons than would be possible in the older method. There is one difficulty, however, that must be taken into consideration. If the exposures are such that the images of faint stars (say, of the twelfth magnitude) are adequately recorded on the photographic plate, it follows that the image of the "parallax" star, which is generally much brighter than the faint "comparison" stars, will be very much larger than the images of the latter stars and therefore much more difficult of accurate measurement; the errors of measurement, in fact, may be out of all proportion to the small angle of parallax which it is attempted to measure. This difficulty is surmounted in modern investigations by various devices, the effect of which is to reduce the brightness of the "parallax" star to approximate equality with the "comparison stars."

Between 1903 and 1907 Professor H. N. Russell and Mr A. R. Hinks at Cambridge measured the parallaxes of 52 stars from photographs taken with the Sheepshanks refractor. To-day, about a dozen of the great observatories all over the world are assiduously engaged in throwing out the fathom line in all directions, sometimes touching bottom and adding to our store of knowledge of stellar distances. The rate of progress in this field is naturally slow. A single determination of parallax requires the measurement of at least a dozen plates, half of them separated by an interval of about six months from the remainder, each plate having two or three distinct exposures. At the Royal Observatory, Greenwich, a steady output of about 50 parallaxes per year is being maintained; this involves the taking of eight or nine hundred plates in the course of the year. The General Catalogue of Parallaxes, compiled in 1924 by Professor Schlesinger, now of Yale Observatory, contains 1870 entries; in 1928 the number of trigonometrical parallaxes is probably well over the 2500 mark.

It is safe to say that the modern photographic methods are able to detect with certainty a parallax of $0''\cdot01$; the most powerful telescopes have sounded space to much greater depths and measured parallaxes of $0''\cdot005$ have claims to be considered reliable. It is well to ponder for a little on the achievements of modern astronomy. A parallax of $0''\cdot01$ is the angle subtended by the radius of the earth's orbit at a star whose distance from the sun is 20 million times 93 million miles;

in light-time, this distance is equivalent to 326 light-years. This means that the light from a star of parallax 0″·01 which impressed a photographic plate in 1926, had been silently traversing the immensities of space since 1600 with the mighty speed of 186,000 miles per second.

Marvellous indeed are the achievements of astronomy in the domain of precise measurement but there are limits of space unpenetrated and at present impenetrable by the direct trigonometrical method we have just described, for parallaxes smaller than 0″·001 (corresponding to a distance of 3260 light-years) are beyond the reach of the most powerful telescopes. The exploration of the distant regions of space depends on indirect methods, but it must be emphasised that these methods are built on the sure foundation of the known distances of the nearest stars.

The following table has been compiled from Schlesinger's Catalogue of Parallaxes; it gives the number of stars between certain successive limits of parallax, stopping at the comparatively large parallax of 0″·05. The table represents the state of knowledge as regards the nearest stars in 1924; it comprises 309 stars, about one-sixth of the total number of entries in the Catalogue.

TABLE GIVING NUMBER OF STARS BETWEEN VARIOUS LIMITS OF PARALLAX.

| | Number. | | Number. |
|---|---|---|---|
| Over 0″·40 | 2 | 0″·09 to 0″·10 | 19 |
| 0″·30 to 0″·40 | 7 | 0″·08 ,, 0″·09 | 22 |
| 0″·25 ,, 0″·30 | 8 | 0″·07 ,, 0″·08 | 40 |
| 0″·20 ,, 0″·25 | 6 | 0″·06 ,, 0″·07 | 59 |
| 0″·15 ,, 0″·20 | 18 | 0″·05 ,, 0″·06 | 85 |
| 0″·10 ,, 0″·15 | 43 | | |

Stellar distances are so great that ordinary terrestial units of length are clumsy and unwieldy. The light-year is one unit in use, particularly in non-technical writings; we have seen that a parallax of 1″ represents a distance which is expressed as 3·26 light-years; this distance in miles is actually 19 million million miles, so that one light-year represents a distance of nearly

6 million million miles. The unit of length employed by astronomers is the *parsec*—that distance which corresponds to a parallax of 1″. A parsec is thus just over 19 million million miles. A parallax of 0″·1 thus represents a distance of 10 parsecs, a parallax of 0″·01 a distance of 100 parsecs, and so on.

The knowledge of the distances of the stars enables us to take another step forward in elucidating their individual characteristics. As we have seen in a previous chapter, the apparent brightness of a star will appear five magnitudes fainter if it is removed to ten times its present distance. The knowledge of a star's distance and its apparent magnitude allow us to calculate what its apparent magnitude would be if it were placed at any particular distance from us. To compare the luminosities of the stars, we must calculate what their magnitudes would be if they were all at equal distances from us. It is, of course, immaterial what particular distance is chosen; actually, the distance usually chosen by astronomers is 10 parsecs (or 32·6 light-years), corresponding to a parallax of 0″·1, and the stellar magnitudes calculated for this distance are called *absolute magnitudes*.

When this is done, it is found that the range in absolute magnitudes is extraordinarily great. Let us compare the absolute magnitudes of two of our nearest stars. Sirius, the brightest star in the heavens (apparent magnitude 1·6), with the large proper motion of 1″·3 per annum and the large parallax of 0″·37, would appear as of magnitude 1·2 at the distance of 10 parsecs, that is to say, the absolute magnitude of Sirius is 1·2. Barnard's 'runaway' star is a faint star of apparent magnitude 9·7; its proper motion is the greatest hitherto found (10″·3 per annum); with the exception of the physical system of α Centauri, it is our nearest stellar neighbour (parallax 0″·54); a simple calculation shows that its absolute magnitude is 13·2, that is to say, at a distance of 10 parsecs it would appear as of magnitude 13·2. What do these absolute magnitudes show us? For these two stars the difference in absolute magnitudes is 12·0, which represents a ratio of luminosity of 60,000 to 1. Compared with Sirius, Barnard's star is a feeble member of the stellar host; compared with Barnard's star, Sirius is an orb of transcendent brilliancy.

# CHAPTER XII

## THE SPECTROSCOPE AND THE STARS

In Chapter VI we described, in some detail, the spectroscope, its application to the sun and the interpretation of the solar spectrum according to modern atomic theory. In this chapter we shall turn the instrument on the stars themselves, and from their light messages learn their secrets. At the outset it is well to recall the nature of light radiations and the principles which form the basis of spectrum analysis.

The main characteristic of a star is that it is a self-luminous body, emitting streams of heat and light. The sun, in fact, is a star, its astronomical importance to us being due to its comparative proximity to the earth, so that it can be studied more easily and exhaustively than any star in the firmament. But all stars are not facsimiles of the sun, as even a casual glance at the heavens will prove, for amongst a score of the brightest stars, there is a diversity of colour ranging from the unmistakable red of Betelgeuse to the bluish white of Rigel, which can only mean one thing, namely, that the stars are not all built to one definite pattern like the motor-cars of a mass-production factory. This fact was realised more profoundly when the light of several bright stars was first examined in the spectroscope.

Stellar spectroscopes are of two kinds, but each depends on the breaking up of a star's light in its passage through a prism.[1] In one kind, a large prism is placed in front of the object glass of a telescope; the light from a particular star is resolved into its constituent components by the prism and after passing through the object glass is brought to a focus where it can be examined in the ordinary way by an eye-piece or photographed on a sensitive plate. The advantage of this type of instrument is that the spectrum of every star, down to a particular limit

[1] Instead of a prism, a diffraction grating is sometimes used.

Actually, Barnard's star is one of the feeblest luminaries known; Sirius, on the other hand, is surpassed in luminosity by many other stars. Our own sun, were it removed to a distance of 10 parsecs from us, would appear as a star of magnitude 5·0; thus our brilliant sun is a very ordinary member of the stellar host, its intrinsic brightness being only $\frac{1}{33}$ of that of Sirius. The first-fruits of the measurement of stellar distances are the amazing diversities in the luminosities of the stars. At one extreme are the superlatively brilliant orbs, at the other the feebly luminous stars; the former are the *giants* and the latter the *dwarfs*, and within this range are stars of all luminosities. Why is it that one star is intrinsically a million times brighter than one of its brethren? Is it because of vaster size or higher temperature or a combination of both? These are questions that modern astronomy can answer decisively, as will be seen in later chapters.

From the known parallaxes and proper motions we can proceed to investigate another characteristic of the stars, namely, their space motions or rather that part of their motions at right angles to the line of sight. The proper motion gives us the angular rate at which the star is changing its position on the celestial sphere; the knowledge of the star's distance enables us to convert this into linear speed (miles per hour or miles per second). Let us consider two stars, Sirius and Arcturus. The known values of the parallax and proper motion of Sirius, which we have stated earlier, show that, relatively to the sun, Sirius is moving across the line of sight with the great speed of approximately 10 miles per second. Similarly, for Arcturus (with a proper motion of 2″·3 per annum and parallax of 0″·08) the cross-velocity is found to be, approximately, 100 miles per second. The latter is an amazing speed, many times greater than the average for the stars; indeed, the speed of Sirius may be regarded as typical of the stars in general. The cross-velocity is only one component of a star's space-motion; to complete our knowledge of its actual speed in space, we require to ascertain the component in the line of sight, that is, the star's radial velocity. This is the province of spectroscopic astronomy, which will form the subject of a subsequent chapter.

of magnitude depending on the length of the exposure, in the field of the telescope can be photographed on one plate. In the slit spectroscope, only one star can be examined or photographed at a time. The slit is placed in the focus of the telescope, so as to admit the light from the particular star under observation; this light passing through one or more prisms is spread out into a spectrum and finally imprints its message on the photographic plate. The advantage of the latter instrument is that a comparison spectrum, for example, that of glowing iron vapour, can be photographed alongside the stellar spectrum, the lines of the comparison spectrum providing the known landmarks whereby the wave-lengths of the lines of the stellar spectrum may be correctly measured. It is not our purpose to enter into descriptions of instrumental detail and into questions of technique; it is hoped that this brief account will be of some service to the reader in his appreciation of the reproductions of stellar spectra shown in Plate XIV (*a*).

The first observations of a star's spectrum were made visually by Fraunhofer, near the beginning of the last century. It will be remembered that Fraunhofer mapped out several hundred lines of the solar spectrum—the dark absorption lines on the beautiful background of the continuous spectrum—and when he examined in a similar way the light of such stars as Sirius, Castor, Pollux, Capella and so on, he was immediately struck by the differences exhibited by the respective spectra and by that of the sun. But there was one feature common to several of the stars examined—the dark line (or rather the close double line) in the yellow region of the spectrum, due to sodium (the so-called D line), was conspicuous and unmistakable. We now know that the D line is the evidence of the existence of sodium in certain stellar atmospheres, but at the dawn of astrophysics the prominent D line in the several spectra indicated hardly any more than that certain stars had at least some kind of property in common. We have seen that it was only in 1859 that the dark absorption lines in the solar and stellar spectra received a satisfactory interpretation. Henceforward, the identification of the dark lines with the characteristic spectrum lines of the familiar terrestrial elements proceeded apace, proving that the stars as well as the sun were built up of one or more of the elements of which the earth is constituted.

Except for about one per cent. of the stars, stellar spectra are absorption spectra, resembling in this respect the solar spectrum. The spectrum thus consists of a continuous spectrum—the succession of the rainbow colours from red to blue—crossed generally by a large number of fine dark lines. And we have seen in Chapter VI that we are enabled to interpret the dark lines in the solar spectrum as the evidence of an absorbing atmosphere (the reversing layer) lying above the main radiating surface of the sun (the photosphere). For the stars, a similar interpretation holds; only the great diversity in the absorption-line spectra of the stars points apparently to a wide range of differences in the chemical and physical constitution of the stellar atmospheres.

In 1863 Huggins and Miller, at King's College, London, made the first attempts at photographing a star's spectrum, but without success. Nine years later, Dr Henry Draper of New York obtained the first satisfactory photograph of a stellar spectrum, that of Vega, showing several of the more prominent absorption lines. Astrophysics had now got the tool it required and progress soon became amazingly rapid.

One of the functions of the pioneer in science is to produce order out of chaos; of the hundreds of stars whose spectra had been examined visually, hardly two were alike, but clearly some rough kind of classification—if it were at all possible—was a prime necessity. Father Secchi, at Rome, was the pioneer in this department of astronomy. He divided the stars into four broad groups or types, according to their spectra, as follows:—

*Type I* consisted of the blue and white stars in which the dark absorption lines of hydrogen were prominent, and in which there was no trace (or at the most, very little trace) of lines due to metals such as iron, aluminium, etc.

*Type II* consisted of yellow stars in which the numerous dark lines of the metals were conspicuous; in this class were such stars as the sun and Capella.

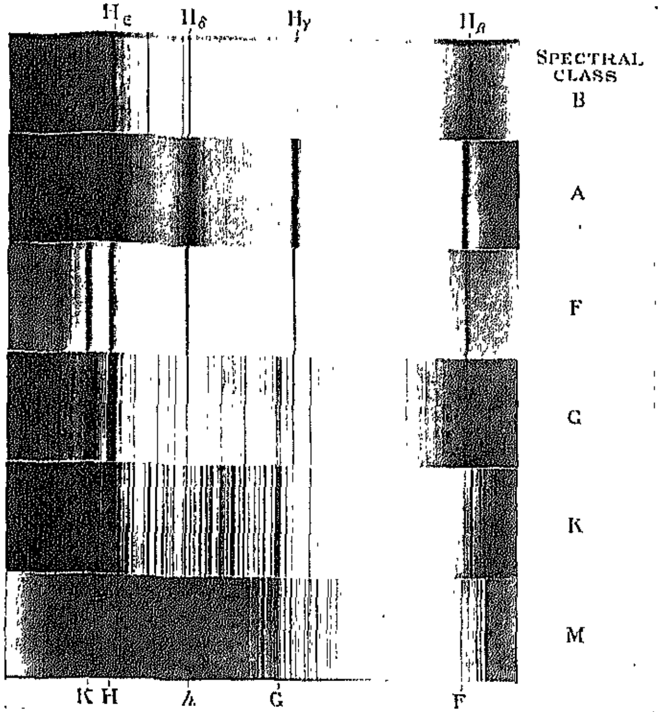
*Type III* consisted of the orange and red stars. Their spectra were conspicuous for dark absorption bands. Antares and Betelgeuse are prominent stars of this type.

*Type IV* included the deep red stars with prominent bands or flutings in their spectra. The members of this class are rather faint and do not include any of the better known bright stars easily visible to the naked eye.

Secchi's classification is, in some respects, a classification according to colour. It must be understood that the spectra of all the stars within a particular class are by no means identical; the classification is on broad grounds and takes no account of the differences within a particular class. Secchi's observations were all made visually, a fact which makes his investigations all the more noteworthy.

With the introduction of photographic methods recording the spectra of the stars, it was possible to make a more detailed sub-division of the classes. At the present time, the classification is that developed, notably by Miss Cannon, at the Harvard Observatory. Roughly a quarter of a million stellar spectra, photographed with an objective prism instrument, have been examined and arranged in classes. The nine large volumes which contain the results have been dedicated as a memorial to Dr Henry Draper—one of the pioneers in stellar spectroscopy—and the classification is generally referred to as the Draper Classification. The principal classes are denoted (in order) by the letters O, B, A, F, G, K, M, R, N and S. Ninety-nine per cent. of the stars are included within the six classes B to M. Each spectrum class is sub-divided: thus a star whose spectrum is in character half-way between G and K is denoted by G5 and one that is nearer G than K is denoted, say, by G2, and so on. Thus all the stars of type G belong to one of the sub-sections G0, G1, G2, . . . G9. The classes B to M form a continuous series, the B type gradually merging into the A type, and so on. We now give a very brief description of the Draper Classification, reserving for the moment our comments on its significance. Typical spectra are shown in Plate XIV (*a*).

*Class B.* The dark lines of hydrogen and helium are prominent. In several stars, the lines of ionised helium—that is, helium which has lost one of its two planetary electrons—are also found. The lines due to ionised silicon, oxygen and nitrogen are also prominent. At B5, the K line of ionised calcium appears and at B9 helium has almost




(*a*) Typical Spectra.
*Harvard Observatory.*

(*b*) Spectrum of *Procyon* (middle); comparison spectrum above and below.
*Mt. Wilson Observatory.*

(*c*) Spectrum of *Mizar* (middle); comparison spectrum above and below.
*Mt. Wilson Observatory.*

completely disappeared from the spectrum. Stars of this class are sometimes called "helium stars" or "Orion stars." Prominent members of this class are: Rigel, Regulus, the bright stars in the Pleiades and several stars in the constellation of Orion.

*Class A.* In spectra of this type, the lines of hydrogen are the most prominent. The lines of several metals, notably those of ionised calcium and magnesium, are in evidence, but weak in comparison with the conspicuous lines of hydrogen. Sirius, Vega and Castor are stars belonging to this class.

*Class F.* In spectra of this class, the hydrogen lines become less prominent and the lines of metals—notably the H and K lines of ionised calcium—gain in importance. Near the end of this class, at F8 and F9, the spectra bear a strong resemblance to the solar spectrum. Typical F stars are Procyon and Canopus, which are white stars.

*Class G.* This is the class to which the sun belongs. The spectrum is remarkable for the enormous number of metallic lines—notably the lines of neutral, that is, un-ionised iron; the lines of hydrogen and of ionised calcium are still prominent. Typical stars are the sun and Capella—both of type G0; these stars are yellow in colour.

*Class K.* Bright stars in this class are Arcturus and Aldebaran. The lines of ionised metals become weaker; the lines of neutral metals become stronger. Near the end of this class, there is evidence of the bands of titanium oxide. The stars of this group are orange in colour.

*Class M.* The important feature of stars of Class M is the great strength of the bands of titanium oxide; the lines of neutral metals are also prominent. The stars in this class are red; Antares and Betelgeuse belong to Class M.

The spectra of the sequence, B to M, are with a few exceptions absorption spectra—that is, each spectrum consists of the rainbow colours red, orange, etc. to violet, crossed by dark lines. In Class O the most important lines are *bright* lines of hydrogen, of ionised helium, carbon, oxygen and nitrogen; there are, in addition, several bright lines of unknown origin. The classes R, N and S may be regarded in some respects as

sub-divisions of Secchi's Class IV—they are red stars and comparatively rare in the heavens.

Intimately related to the character of the spectrum of any particular star is the question of temperature. At one end of the main spectral series we have stars bluish white in colour (Class B), and at the other end (Class M) there are stars unmistakably red in colour. When a poker is placed in a fire it becomes dull red in colour, and if the heat is sufficiently intense it eventually becomes—as we describe it—white hot. In this homely example, there is evidently a very definite relation between colour and temperature. Is there a similar relation governing the temperatures and colours of the stars—in other words, are stars of Class B " hotter " than stars of Class M ? But before we can answer this question in any detail, we must attempt to understand what we mean by " temperature " when applied to the stars. The only bridge between ourselves and a star is the stream of radiant energy (heat and light) emitted by the star in our direction. As we shall see later, the source of a star's energy must lie deep within its interior. It is this internal supply that makes its way towards the surface and, finally escaping from the star's photosphere, is radiated away in all directions into space. It is the escaping energy which is the subject of our measures, and the intensity of this energy is dependent on the " temperature " of the photosphere. But this is not all. Imagine a cannon ball and an equal sphere of lime heated to a temperature of 500° C. Each sphere radiates heat energy across its surface, but there is no *a priori* reason why the intensities should be the same; one is certainly less efficient in this respect than the other, and each falls short of what the physicist describes as a " perfect radiator." If the photosphere of a star is a perfect radiator the laws of physics, combined with the measured intensity of the radiation, lead to a definite value of the photospheric temperature. It is found that the sun and stars are pretty nearly perfect radiators, but we shall not stop to discuss details with respect to any divergency in this respect. We shall assume simply that a star's temperature (that is, the temperature of the photosphere) is deducible from well-established physical laws; this temperature is generally called the *effective temperature*.

Suppose a perfect radiator maintained at a temperature of

5000° C. It radiates heat and light and, according to Planck's law of radiation, the intensity of the radiation varies from wave-length to wave-length in a certain definite manner illustrated in Figure 79. For example, in the case under consideration, the law indicates that the blue end of the spectrum is extremely faint, but that in the red (around wave-length 6000 Å) the intensity is very great and is in fact a maximum near this point (M, in the figure). At the point A of the curve—at wave-length 10,000 Å—the intensity of the radiation corresponding to this wave-length is about three-fifths of the intensity of the

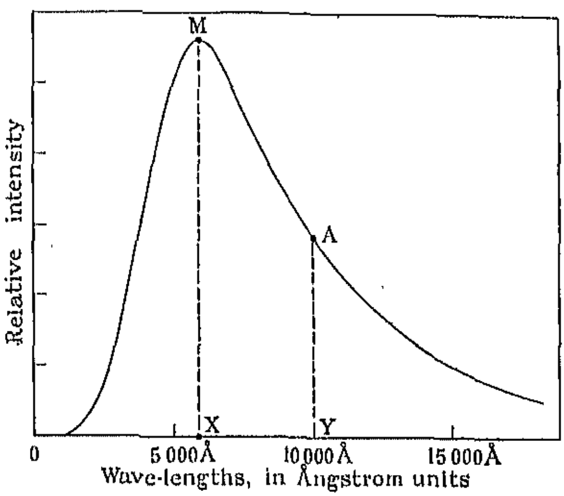



Fig. 79.

radiation corresponding to the wave-length 6000 Å, as measured by the ratio of the lengths YA and XM. If the temperature had been 3000° C. instead of 5000° C., the curve would have been quite different; in other words, a perfect radiator will give a series of curves, each curve depending on the temperature at which it is maintained. The principle of finding a star's effective temperature will now be perceived; it consists in obtaining from observations the measures of the relative intensities of the radiation emitted by the star corresponding to different wave-lengths in the spectrum. These measures can be exhibited in the form of a curve, which is then confronted with the series of Planck curves, an example of which is shown in Figure 79, and

the one to which the observed curve most closely approximates will furnish the value of the effective temperature of the star.

There is a simple modification of the process based on what is known as Wien's law. The theoretical curves (such as Figure 79) have peaks at different wave-lengths; Figure 79, for example, has a peak corresponding to wave-length 6000 Å, and the statement of Wien's law is that the temperature of the radiating body is inversely proportional to the wave-length corresponding to the peak. The observations furnish the wave-length for which the radiation is most intense, and the effective temperature of the star is then deducible directly from Wien's law.

There is a third law of radiation known as Stephan's law, by which the effective temperature of a star can be deduced if the total amount of radiation emitted by the star can be measured.

The radiation from a stellar photosphere gives rise to the continuous spectrum. In stars of Class M the red end of the spectrum is bright and the blue end of the spectrum is faint. The maximum intensity in the spectrum of these stars evidently occurs in the red or infra-red part of the spectrum—in other words, most of the radiation sent out by such stars consists mainly of red light. Again, in stars of Class B, the blue end of the spectrum is the most brilliant, with the red end comparatively faint. But the wave-length of blue light is much shorter than the wave-length of red light; consequently, by Wien's law the effective temperature of a B type star is much higher than the temperature of a star of Class M. Moreover, precise measures of the wave-length at which the maximum intensity occurs in the respective spectra lead to a precise ratio of the effective temperatures of the two stars. The application of these principles is, however, attended by many difficulties. We mention but one. The observations are necessarily conducted at or near the base of the earth's atmosphere, which absorbs incoming light from the stars in different amounts depending on wave-length, blue light much more than red. The effect of the earth's atmosphere has therefore to be allowed for; the measures are, in fact, altered to what it is believed they would be if the stars could be observed without the intervening complications of our atmosphere. It is clear, therefore,

that the estimates of stellar temperatures must on this account alone be somewhat uncertain.

The pioneer work in this department of astrophysics was done nearly twenty years ago at Potsdam. The observations of the intensity of the stellar radiation in the different parts of the spectrum were made visually. Professor Sampson, of the Royal Observatory, Edinburgh, has introduced a photographic method. Let us assume for simplicity that the photographic plate is equally sensitive to light of all wave-lengths, so that, for example, blue light and red light of equal intensities will produce equal darkening on the plate. If the spectrum of a star is photographed on such a plate, the degrees of darkening produced by the different parts of the continuous spectrum bear some definite relation to the different intensities in these parts. For example, in the spectrum of a B type star, the photographic darkening will be conspicuously greater in the shorter wave-lengths (those of blue light) than in the longer wave-lengths (those of red light)—in fact, the plate will be hardly blackened at all in the section which corresponds to the red end of the spectrum. The degree of darkening throughout the spectrum is measured by means of a photometric equipment—into the details of which we need hardly enter here—and so, from the laws of the photographic action of light, the relative intensities of the various wave-lengths in the continuous spectrum of the star can be obtained. Comparison with Planck curves, as in Figure 79, yields the stellar temperature. The difficulties of this method mainly result from the characteristic behaviour of the photographic plates used in the investigation, for no photographic plate is equally sensitive to light of all wave-lengths, as we assumed in our simple explanation. Thus the investigation of stellar temperatures by Professor Sampson's method must be preceded by a careful investigation into the behaviour of photographic plates in relation to the actinic effects of the different kinds of light.

We have had occasion to refer to a very delicate instrument—the radiometer, or bolometer—which is capable of measuring minute quantities of heat radiation. The instruments at Mt. Wilson are reported to be so sensitive that the heat from a candle placed 100 miles away could be detected and measured. With an instrument of this kind, Dr C. S. Abbot has succeeded

in measuring the actual amounts of radiant energy in the different parts of the spectra of several of the brightest stars. The observations made on any one star then give a curve which expresses the relation between the intensity of the radiant energy and the corresponding wave-length ; this observed curve is then compared with the series of Planck curves (as in Figure 79), and the star's effective temperature is deduced in the manner already explained.

In all these methods of deriving estimates of stellar temperatures, only one feature of the spectrum has been submitted to investigation, namely, the continuous spectrum. But a star's spectrum consists of more than the continuous spectrum ; in many respects, the most characteristic feature of the spectrum is the system of dark absorption lines. We shall now try to explain how these lines can be utilised in furnishing an independent measure of a star's temperature. In considering absorption lines we are concerned with the chemical constituents of the star's atmosphere and the physical conditions of temperature and pressure in which the various elements can exist. Let us glance back at the classification of stellar spectra. The classification is based mainly on the nature of the absorption lines—in other words, it is a classification, partly, at least, according to the nature of the stellar atmospheres. As we pass the various spectral classes in review, we see that at one extreme (Class O and B) the hydrogen and helium lines are the most prominent, while at the other end (Class M) these two light gaseous elements are inconspicuous ; moreover, in Class M, the bands of chemical compounds overshadow everything else. Does this mean that in the stars of Classes O and B the atmospheres consist mainly of hydrogen and helium, while in stars of Class M these two gases are not prominent constituents of the atmosphere ? Again, why is the existence of chemical compounds possible, as judged by the spectra, in the atmospheres of some stars and not in the atmospheres of others ? The questions we have asked depend for an adequate answer on something more than the consideration of the chemical constitution of the stellar atmosphere. As we shall see, the conditions of pressure and temperature are of paramount importance in our interpretation of the line spectra of the stars. The problem, in fact, concerns the behaviour of the

individual atoms of an element under the physical conditions in which they find themselves in the stellar atmospheres. Let us consider the element iron. In the spectra of G type stars, the absorption lines of iron are conspicuous. In the atmospheres of these stars (including the sun) the atoms of iron vapour are subjected to the intense stream of radiant energy passing outwards from the photosphere. A particular atom absorbs a particular packet of this energy; its outermost electron (or electrons) jumps to a higher orbit (that is, one more distant from the nucleus) depending on the particular wave-length of the photospheric radiation which it has swallowed. The atom remains but a brief time in this state. The active electron jumps back from the outer orbit to a lower orbit emitting radiation of a wave-length depending on the two orbits concerned. But here we notice a difference. The radiation which the atom absorbs is pouring outwards from the star's interior; the radiation which the atom emits may be fired off in any direction, outwards or inwards, and thus only a fraction of the energy re-emitted by the iron atoms escapes from the star. These are, briefly, the atomic processes according to which the existence of absorption lines in the stellar spectrum is explained. Let us now imagine that the photospheric radiation is of such a quality that a certain proportion of the iron atoms will lose their outermost electron—in these circumstances, the atoms are ionised. Now we have seen in Chapter VI that the spectrum of an ionised element is distinct from the spectrum given by the complete atoms; consequently, under the circumstances which we imagined, there will appear in the stellar spectrum new lines due, in fact, to ionised iron. This is precisely what is found in the spectra of stars of Class F, and we must therefore conclude that, for these stars, the temperature and pressure conditions are such that a certain proportion of the iron atoms, at any given instant, are each shorn of one electron. We can now go one step further and suppose that the photospheric radiation and the physical conditions in the stellar atmosphere are such that the great majority of the iron atoms are ionised. The remnant of the neutral (or un-ionised) atoms can achieve but a feeble amount of absorption, and the corresponding lines in the spectrum will be inconspicuous or "weak." But the ionised atoms—now in the majority—will strongly absorb the photo-

spheric radiation in their own distinctive wave-lengths and the corresponding lines will be prominent or "strong." Let us go one step further and imagine that no single atom of iron can retain its complete array of electrons. The atoms are then all singly ionised and the spectrum will not contain the least trace of the ordinary or neutral iron lines; it will of course contain the lines characteristic of the ionised atoms. It must be remembered that the part of the stellar spectrum that we can see or that we can photograph represents only a portion of the complete range of wave-lengths of radiation. Iron happens to be an element which in its neutral and singly-ionised states has characteristic series of lines in the ordinary region of the spectrum with which we are familiar in astrophysics. Some other elements behave differently; the chief lines corresponding to the singly-ionised state of the atom fall outside the region that can be photographed and therefore if the physical conditions in the stellar atmosphere are such that all the atoms of such an element are ionised, there is not the slightest indication in the spectrum that this element is present in the star's atmosphere. So it may be with doubly and trebly ionised atoms. When we examine the spectra of the hottest stars and see very little evidence of the elements, except hydrogen and helium, as revealed by the spectrum lines, we must not exclude the possibility that some of the elements may all the time be present in the stellar atmosphere, their atoms being in a highly ionised state and their messages being in wave-lengths to which our instruments cannot be tuned. Moreover, in stars of Class O, there are lines of unknown origin. Do we interpret the existence of these lines as signifying the presence in the atmospheres of these stars of elements hitherto undiscovered in terrestrial sources? Or do we interpret these lines in the sense that they are due to familiar terrestrial elements existing in the stars in unfamiliar conditions? Physicists and chemists believe that the tale of the elements is almost entirely complete and therefore the conclusion seems to be definite that the unknown lines are simply the evidence of one or more known elements existing in a higher state of ionisation than that to which it is possible to reduce them with our present laboratory methods, or existing in circumstances that cannot be imitated in the laboratory. The problem of their origin will very likely be solved in the

immediate future either by the experimental physicist in subjecting the known elements to a more intense ionising agency, or by the mathematical physicist who may be enabled to deduce from the laws of atomic physics the particular element or elements responsible for the lines.

Let us examine more carefully the physical conditions in stellar atmospheres in relation to the ionisation of the atoms. The higher the temperature of the stellar photosphere, the more powerful is the ionising agency. But if the elements are tightly packed together, as in gases of high density, an electron is no sooner expelled from one atom than it is captured by another. High temperature and high density combined are consequently not the ideal conditions for ionisation. If the pressure is very low, that is, if the atoms are sparsely scattered, an expelled electron has much less chance of capture and a certain proportion of the atoms will remain ionised. In Chapter VI we made reference to Saha's theory, which can predict the varying proportion of atoms of a given element which are ionised under different temperature and pressure conditions. In particular, if the pressure is assumed to be known, the temperature at which all the atoms of an element are ionised can be calculated. When we apply this theory to stellar atmospheres we notice, for example, in proceeding from stars of Class G to Class F and Class A, that there is a definite type of spectrum in which the iron lines are entirely due to the singly-ionised atoms. Assuming the pressure to be known, we can therefore calculate the temperature which is just sufficient to account for the complete ionisation of the iron atoms. A similar calculation of temperature can be made, for example, in the case of a spectrum in which the lines of the neutral and ionised atoms are of equal strength. This brief explanation is perhaps sufficient to enable the reader to catch a glimpse of the principles of this method. Later work by Mr R. H. Fowler and Professor E. A. Milne in the development of Saha's theory has resulted in the establishment of stellar temperatures in very good agreement with the values obtained by other methods. The following table exhibits the results obtained by Professor Sampson and by Messrs Fowler and Milne. It may be remarked that exact agreement can hardly yet be expected in this difficult branch of astronomical physics, but it must be admitted that the accordance

of the estimates for the different spectral types in this table (and of the estimates of other workers) is impressive as well as remarkable.

TABLE OF STELLAR TEMPERATURES.

| Spectral Type. | Sampson. | Fowler and Milne. |
|---|---|---|
| O5 | — | Higher than 35,000° C. |
| Bo | 25,000 | 26,500 |
| Ao | 13,100 | 10,000 |
| Fo | 8,900 | 7,500 |
| Go | 6,200 | 6,000 |
| Ko | 4,200 | 4,500 |
| Mo | 3,400 | 3,000 |

In addition to temperature, there is a second factor, the gas pressure in the stellar atmosphere which influences spectral type, and we shall see in a subsequent chapter what are the effects of the latter factor. It may be remarked here that the pressures in the stellar atmospheres are generally a minute fraction of the pressure with which we are familiar in our own terrestrial atmosphere.

The classification of stars according to spectral type is seen to be mainly a classification according to temperature. The spectral sequence (B, A, . . . M) is a series of descending temperature. Also colour and spectral type are closely associated; we conclude that the bluish-white stars are the hottest and the red stars the coolest. Moreover, when the various spectral types are considered in greater detail, many problems that at first sight appeared baffling are seen to be simply resolved by the light now thrown upon the atomic processes in relation to the ascertained physical conditions existing in stellar atmospheres. It is indeed a marvellous achievement that the temperature of stars, tens and hundreds of light-years away from us, can be measured with such remarkable precision. It is here that the astronomer can come to the aid of his brother in the physical laboratory, for, in the hottest stars, matter exists under conditions unequalled in the laboratory and the study of stellar spectra leads to the more intimate knowledge of the structure and behaviour of the atom, which is the main field of research in physics to-day.

# CHAPTER XIII

## The Motions of the Stars in the Line of Sight

We consider in this chapter one astronomical application of the study of stellar spectra. In Chapter VI we explained what is known as Doppler's principle and referred to its application to the measurement of the rotation of the sun. Briefly it is this: if we are travelling towards a light source which is emitting light waves of a particular wave-length in our direction, we shall meet more light waves per second than if we were stationary. The effect is thus to shorten the wave-lengths of the light. If we are receding from the source, the effect is, similarly, to increase the wave-lengths of the light. Now we have mentioned that when a stellar spectrum is photographed a comparison spectrum of iron vapour, for example, is photographed alongside of it. The iron lines form a standard of reference for the measurement of the lines of the stellar spectrum. If the star is moving towards us, every wave-length of the star's light will appear shorter than it would be if we and the star had no motion towards each other. Suppose the star's spectrum to contain iron lines; then the effects of the relative motion of ourselves and the star results in the displacement of each of the star's iron lines relatively to the corresponding line of the comparison spectrum and this displacement is towards the shorter wave-length, that is, towards the violet. If we and the star are separating, the displacement of the stellar lines is towards the red end of the spectrum. The amount of the displacement depends on the ratio of the star's velocity of approach (or of recession) to the velocity of light and also on the particular wave-length considered. Plate XIV (*b*) shows the spectrum of the star Procyon with the comparison spectrum alongside; the relative displacements of the various lines common to the two spectra are plainly visible. These displacements are carefully measured and the displacement of

a particular line can then be expressed as so many Ångstrom units. For example, if the measured displacement of a line, whose wave-length in the comparison spectrum is 5000 Å, can be represented as 5 Å, the velocity of the star towards us or away from us is 186 miles per second. If the displacement of the line is towards the red, for example, the star's velocity is one of recession. This particular component of a star's velocity, which is measured by the displacement of the spectrum lines, is called the line-of-sight velocity or the *radial velocity*. The radial velocities of several thousand stars have already been measured and this kind of work is still being actively pursued, notably at the Victoria Observatory in British Columbia and at the great observatories in the United States.

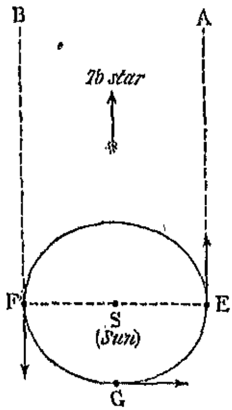


FIG. 80.

Let us now consider some of the investigations which are based on a study of radial velocities. We take first the measurement of the earth's distance from the sun. This, as we have seen in the earlier part of the book, is the fundamental astronomical unit of length, and astronomers have seized every opportunity of determining this unit in terms of the earth's radius or of the familiar terrestrial unit, namely, the mile. It seems at first somewhat remarkable that the earth's distance from the sun can be measured by means of spectroscopic observations of the stars, but a little reflection will enable us to see why it is really possible. Our observations are made from the earth, which makes a yearly revolution round the sun at a certain average speed. If the spectroscope can tell us what this speed is, the earth's distance from the sun can be easily calculated. Let us make the problem as simple as possible. In Figure 80, let the curve represent the earth's orbit around the sun and let E be the position of the earth in its orbit, say, on March 1 and F its position on September 1, six months later. Suppose, further, that we photograph the spectrum of a star whose direction lies in the plane of the earth's orbit and is at right angles to the direction of the sun on these dates. EA is then the direction

of the star from the earth on March 1 and FB (drawn parallel to EA) the direction of the star on September 1. In this kind of investigation the minute difference in the directions of the star on March 1 and September 1, due to parallax, may be ignored. Let us further assume for the moment that the sun and the star have no motion relative to each other in the line of sight, so that from this point of view we may regard the sun and star as fixed points. But the figure shows that when the earth is at E, it is moving towards the star with a certain velocity; the spectrum of the star will consequently show a displacement of the spectrum lines towards the violet as compared with the lines of the comparison spectrum, and therefore the measurement of this displacement will furnish the value of the earth's velocity in the direction EA. This is the orbital velocity of the earth, and as it can be expressed in miles per second the dimensions of the orbit can be easily deduced, for we know how many seconds are required for a complete revolution. Actually, the circumference of the orbit, in miles, is the orbital velocity (in miles per second) multiplied by the number of seconds in the year. And so the astronomical unit of length can be found—it is of course the radius SE. We can make the problem more general by omitting the assumption that the sun and star have no relative motion in the line of sight. If the star is, for example, receding from the sun, the spectrum observations made on March 1 (the earth being at E) will clearly give the star's velocity of recession *minus* the earth's orbital velocity in the direction EA; while the spectrum observations made on September 1 (the earth being then at F) will give the star's velocity of recession *plus* the earth's orbital velocity in the direction of the arrow at F. The mean of the two observed spectrum velocities is of course the star's velocity of recession and the difference is twice the earth's orbital velocity. The latter velocity being deduced in this way, the value of the astronomical unit of distance is obtained as before. When all restrictions are removed, which we imposed merely to reduce the method to its simplest aspects, the problem of measuring the astronomical unit of distance remains essentially simple. In May 1927 Dr Spencer Jones, of the Cape Observatory, published a determination of this fundamental unit, based on numerous spectrograms of some score of bright stars. The

diagram (Figure 81), due to the late Professor Lewis Boss, shows the position of the cluster stars on a stellar chart; the arrows drawn from each star represent the directions in which the proper motions are carrying the stars across the sky. The diagram shows that all these directions converge to a certain point in the heavens, called the convergent point, whose position can be accurately found from the proper motion data of all the stars concerned. The interpretation of this diagram is that the converging of the proper motions is due to perspective, that in fact the several stars are moving in space in parallel directions, like the ships in a fleet, and parallel to the direction between us and the convergent point; further, the very likely assumption is made that they are all moving with the same speed. The brightest star of the group is of the fourth magnitude: its radial velocity can be measured very accurately. Let us see how this information leads us to a knowledge of the distances of the individual stars of the cluster. In Figure 82, let S be the position of the sun regarded as fixed, for the proper motion of a star and its radial velocity are both expressed relatively to the sun, just as if they had been measured by an observer situated on the sun. Suppose A to be the star whose radial velocity has been measured. The length of the line SA represents the distance of the star from the sun expressed in miles, or parsecs or light-years. Let us now consider the position of the star A after an interval of a century. If the star's only velocity relatively to the sun were its radial velocity (in round figures we shall take the latter to be 25 miles per second—very close to the measured radial velocity of one of the brightest stars of the cluster), then after a century the star would be at B such that the distance AB in miles is 25 multiplied by the number of seconds in a century. But the actual direction

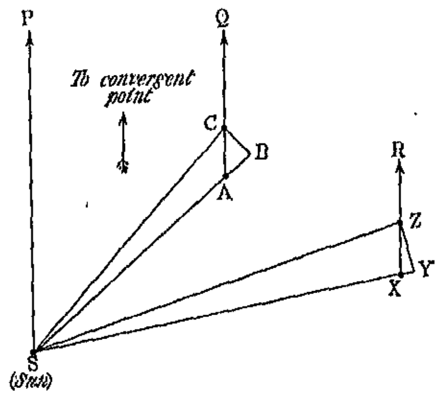



FIG. 82.

a particular line can then be expressed as so many Ångstrom units. For example, if the measured displacement of a line, whose wave-length in the comparison spectrum is 5000 Å, can be represented as 5 Å, the velocity of the star towards us or away from us is 186 miles per second. If the displacement of the line is towards the red, for example, the star's velocity is one of recession. This particular component of a star's velocity, which is measured by the displacement of the spectrum lines, is called the line-of-sight velocity or the *radial velocity*. The radial velocities of several thousand stars have already been measured and this kind of work is still being actively pursued, notably at the Victoria Observatory in British Columbia and at the great observatories in the United States.

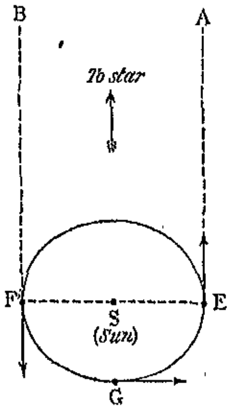



Fig. 80.

Let us now consider some of the investigations which are based on a study of radial velocities. We take first the measurement of the earth's distance from the sun. This, as we have seen in the earlier part of the book, is the fundamental astronomical unit of length, and astronomers have seized every opportunity of determining this unit in terms of the earth's radius or of the familiar terrestrial unit, namely, the mile. It seems at first somewhat remarkable that the earth's distance from the sun can be measured by means of spectroscopic observations of the stars, but a little reflection will enable us to see why it is really possible. Our observations are made from the earth, which makes a yearly revolution round the sun at a certain average speed. If the spectroscope can tell us what this speed is, the earth's distance from the sun can be easily calculated. Let us make the problem as simple as possible. In Figure 80, let the curve represent the earth's orbit around the sun and let E be the position of the earth in its orbit, say, on March 1 and F its position on September 1, six months later. Suppose, further, that we photograph the spectrum of a star whose direction lies in the plane of the earth's orbit and is at right angles to the direction of the sun on these dates. EA is then the direction

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velocity of light (in miles per second) must of course also be known before the displacements of the spectrum lines can be converted into velocities ; the accurate value of this constant given by the experiments of Professor Michelson in 1926 was available for Jones' investigation, and his result must be regarded as one of the most accurate hitherto obtained. Conversely, if the radial velocity of any star is measured several times during the year, the various measures will differ by amounts depending on the varying effect of the earth's orbital velocity. This effect can be calculated (as also that depending on the earth's rotation) for any single measurement of radial velocity, and when applied

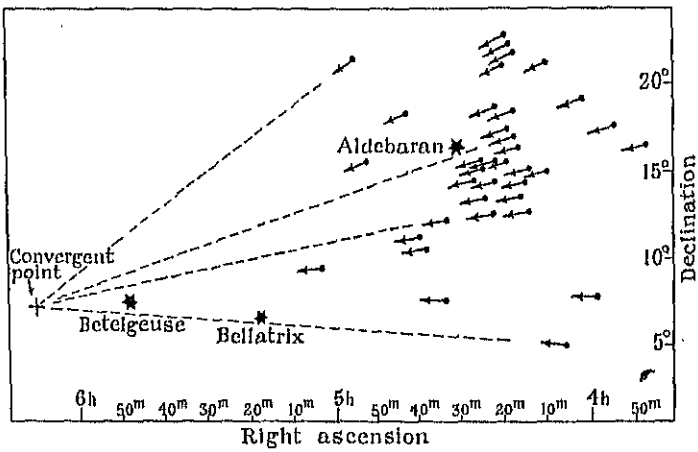



FIG. 81.—MOVING CLUSTER IN TAURUS (BOSS).

to the latter, the star's radial velocity relative to the sun is obtained. We shall assume hereafter that such corrections have been made so that the term *radial velocity* means the velocity, of approach to or of recession from the sun, of the particular star or heavenly body under consideration.

Let us take as a second application of the measurement of radial velocities, the measurement of the distances of the stars in the Taurus cluster. This is a cluster of stars scattered about in the constellation of the Bull. They are distinguished from the hundreds of other stars in the constellation by this common characteristic—their proper motions, of the distinctive amount of about 10 to 12 seconds of arc per century, are all directed towards a definite point of the heavens. The accompanying

diagram (Figure 81), due to the late Professor Lewis Boss, shows the position of the cluster stars on a stellar chart; the arrows drawn from each star represent the directions in which the proper motions are carrying the stars across the sky. The diagram shows that all these directions converge to a certain point in the heavens, called the convergent point, whose position can be accurately found from the proper motion data of all the stars concerned. The interpretation of this diagram is that the converging of the proper motions is due to perspective, that in fact the several stars are moving in space in parallel directions, like the ships in a fleet, and parallel to the direction between us and the convergent point; further, the very likely assumption is made that they are all moving with the same speed. The brightest star of the group is of the fourth magnitude: its radial velocity can be measured very accurately. Let us see how this information leads us to a knowledge of the distances of the individual stars of the cluster. In Figure 82, let S be the position of the sun regarded as fixed, for the proper motion of a star and its radial velocity are both expressed relatively to the sun, just as if they had been measured by an observer situated on the sun. Suppose A to be the star whose radial velocity has been measured. The length of the line SA represents the distance of the star from the sun expressed in miles, or parsecs or light-years. Let us now consider the position of the star A after an interval of a century. If the star's only velocity relatively to the sun were its radial velocity (in round figures we shall take the latter to be 25 miles per second—very close to the measured radial velocity of one of the brightest stars of the cluster), then after a century the star would be at B such that the distance AB in miles is 25 multiplied by the number of seconds in a century. But the actual direction

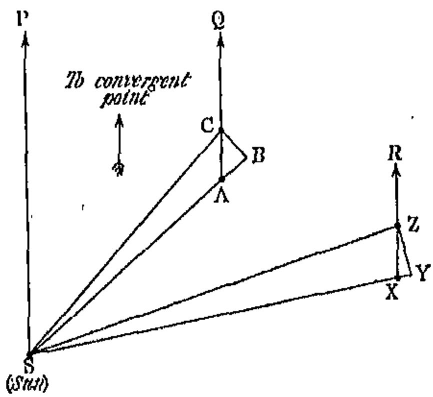



FIG. 82.

of the star's motion is parallel to SP, which is the known direction of the convergent point—that is to say, the star must be at some point of AQ, which has been drawn parallel to SP, after a century's interval. Also a star's motion in space (relatively to the sun) is a combination of its radial velocity with its velocity at right angles to the line of sight. Let BC be drawn perpendicularly to SB. Then after a century, the star must be at C—on AQ. The angle PSA can be calculated, for the directions of SA and SP are known. This gives the angle CAB. Now AB has been found, as we have seen, in miles: the geometry of the triangle CAB yields the value of the side BC and of the side AC both expressed in miles. Now we make use of the known proper motion of the star—call it 12 seconds of arc per century. This means that the angle CSA (or CSB) is 12 seconds of arc. The geometry of the triangle CSB leads to the value of the distance SC in miles—in other words, we have succeeded in measuring the distance of the star. The assumption that the stars of the group are all moving with the same velocity enables us to measure the distances of every one of them. For if X is the position of a cluster star, after a century it must be at Z (XZ is parallel to SP), for the distance XZ is known—it is equal to AC, which, we have seen, we can find in miles. As before, the angle PSX can be calculated: therefore we know the angle ZXY. Hence we can calculate the length YZ in miles and from the observed value of the proper motion, that is the angle ZSY, we deduce the distance SZ.

As the various observed quantities which are taken into account in this problem have been measured with very considerable accuracy, the distances of the stars in the Taurus cluster are amongst the most accurately known. About 80 stars—so far discovered—the faintest about the tenth magnitude, are members of the cluster. In space, these stars form a nearly spherical cluster, about 20 to 30 light-years in diameter, and at a distance from us of 135 light-years. Thus when we see one of these stars in 1928, we are receiving a light message that has been silently on its way through the vast solitudes of interstellar space since the early days of the French Revolution.

We have seen in Chapter XI that the measured proper motions of the stars enable us to fix a certain direction in space

in which the sun is moving as an individual in relation to the general swarm of the stars concerned. The spectroscope enables us to complete this information by assigning the amount of this motion expressed in miles per second. The reader will remember that the solar apex—the direction in which the sun and its retinue of planets is moving—is not far removed from the direction of the star Vega. Suppose we measure the radial velocities of a hundred stars all situated on the celestial sphere in the immediate neighbourhood of the solar apex, and the radial velocities of a hundred stars all situated in the neighbourhood of the opposite point of the celestial sphere. We thus have two groups of stars and we can immediately calculate the average radial velocity of each of the groups. Let us make a further simplification and regard the two groups as at rest relatively to each other, like two mediæval armies on the night before a battle. But the sun is moving towards the first group (that situated in the direction of the solar apex) with a speed which must be that of the average radial velocity of all stars in the group; or expressed in another way, this group will appear to be approaching us with a certain definite velocity. In the same way, the second group will appear to be receding from us with an equal velocity, for we have assumed that the two groups have no motion relatively to each other. Putting the matter in a more general way we should expect that all the stars, whose directions in the sky are nearer the direction of the solar apex than the opposite direction, would give, in the average, a radial velocity towards the sun and the remainder of the stars a radial velocity away from the sun. By a mathematical calculation based generally on the principles just briefly outlined, the motion of the sun relatively to the group of stars scattered all over the heavens—for which radial velocities have been measured, is found to be nearly 20 kilometres per second or 12 miles per second. Incidentally, the calculation gives, in addition to the speed of the solar motion, the direction of the solar apex. This should agree with the position found from the proper motion data alone. Actually, the two methods give slightly different results (there is a difference of about 4 or 5 degrees in the two separately calculated positions of the solar apex—mainly in declination—when the bright stars alone are considered). It must be remarked,

however, that the two methods are not applied to the same stars; for of the stars down to the sixth magnitude in brightness scarcely half have had, so far, their radial velocities measured, whereas practically all have had their proper motions measured.

In a previous chapter, the phenomenon of star-streaming was described from the evidence furnished by the proper motions of the stars. It is possible to derive the characteristics of the two star-streams from a study of the radial velocities, and such investigations confirm the general conclusions reached by examining the proper motion data in the way already described. There are two points of difference in the two methods. The proper motions of stars in almost any limited region of the sky (for example, of stars that can be photographed on a single plate) show up the features of the two streams unmistakably; whereas the radial velocities of stars in two or more widely separated areas of the sky must be compared amongst themselves, before the characteristics of the phenomenon can be disclosed. In the second place, it is only the apparently bright stars that, as a rule, have had their radial velocities measured; and as apparent brightness is no sure criterion of distance (a large proportion of naked-eye stars are at incredibly great distances from the sun), the stars selected for the measurement of radial velocity form a rather scattered company. It is unnecessary to go into the details of the method whereby the radial velocities are made to exhibit the existence of star-streaming; it is sufficient to state that the radial velocities corroborate the results found from the proper motion data alone.

When the actual values of the radial velocities of the stars are examined, several features are noticed. The radial velocities of the great majority of the stars are round about 10 miles per second in value. Although this figure may be taken as typical of the stars in general, there are many stars approaching us or receding from us with vastly greater speeds. Several stars are known with radial velocities exceeding 200 miles per second and the greatest radial velocity of a star so far measured is almost 250 miles per second. Again, the radial velocities so far considered express the speeds with which the stars are moving away from or towards the sun. But the sun is but one star in

the stellar system and by making allowance for the solar motion, we evidently obtain the values of the radial velocities if it had been found that the sun were motionless with regard to the swarm of stars of which it is a member. When the average of the radial velocities (used in the sense just defined) is taken for stars in each of the spectral classes B to M, a remarkable progression in the values of the relative velocities is found, as shown in the following table due to Dr Plaskett.

| Spectral Class. | Average Radial Velocity. |
|---|---|
| B . . . . . | 6·5 kms. per sec. |
| A . . . . . | 10·9 ,, |
| F . . . . . | 14·4 ,, |
| G . . . . . | 15·0 ,, |
| K . . . . . | 16·8 ,, |
| M . . . . . | 17·1 ,, |

The radial velocity is, however, only one component of a star's actual velocity in space. The other part—the transverse velocity—can be obtained when we know the proper motion and the distance of the star. But when we are concerned with large numbers of stars scattered all over the sky, the progression in radial velocity, as shown in the table above, must be representative of the space-velocities of the stars. We have seen that the spectral series B to M is a series of descending temperature; the table then indicates this surprising fact that the average space velocities of the hot B type stars are the lowest, with the average velocities increasing as we pass from the hot B type stars to the much cooler M class stars.

# CHAPTER XIV

## DOUBLE STARS AND VARIABLE STARS

THE founder of Double Star Astronomy is Sir William Herschel. It is true that double stars had been discovered more than a century before his time—the bright star Mizar in the Great Bear was seen to be a double star by the Italian astronomer Riccioli in 1650, and a few discoveries of a like nature were made in later years—but the first systematic search of the heavens for double stars was made by Herschel with a certain definite object in view, and the first evidence of the physical characteristics of many of these objects was given and interpreted by that illustrious and indefatigable astronomer Herschel, at the threshold of his career, embarked on what was in those days the most intractable problem of observational astronomy, namely, the measurement of stellar distances. The method which he intended to follow has already been described at the beginning of Chapter XI and illustrated in Figure 78. Herschel then set himself the task of searching the heavens for pairs of stars answering this description. In 1782 he published his first catalogue of double stars, 269 in number. As we know, Herschel never succeeded in his original design of measuring the distance of a star—this great achievement was reserved for a later generation—but he made a discovery of absorbing interest. By 1797 he had re-measured many of the double stars observed several years previously, and by comparing the new and the old measures, he had indisputable evidence of change in several of these objects. Such a change might be due to the proper motion of one or other of the stars, causing an alteration in the angular separation and in position angle; this might be expected to be the case for two stars almost in the same line of sight (and thus appearing close together in the telescope) but at vastly different distances from us. A double star of this type is called an optical double.

But subsequent observations showed Herschel that this explanation could not be maintained in several instances and that there was clear proof of orbital motion indicating a real bond of attraction between the two stars. Gravitation held the planetary system in its sway: Herschel's observations showed that in the depths of space the same or a similar law was obeyed. A double star of this kind is generally known as a *binary*.

The brighter member of a double star system is called the *primary* and the fainter is called the *companion*. The angular separation of the two components is known simply as the distance. For very close doubles, the distance may be as little as one-tenth of a second of arc, which is practically the limit attainable by the best telescopes and the most skilled observers. There is one other measurement that has to be made before the position of the companion relatively to the primary can be completely specified.

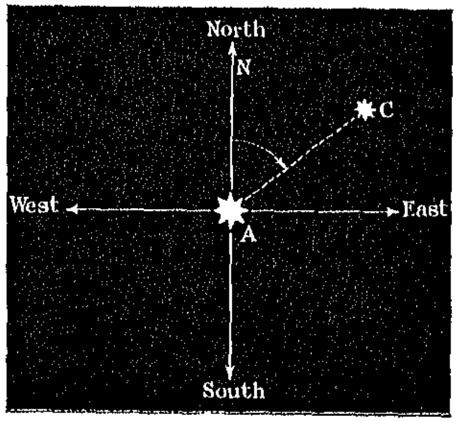



FIG. 83.

In Figure 83, let A denote the primary or the brighter component and C the position of the companion. In the field of view of the telescope AN represents the direction of the north pole of the heavens from A. The angle between AC and AN is called the position angle and is measured from 0° to 360° in the direction indicated by the arrow in Figure 83. The complete observation of a double star consists, then, in measuring the distance AC (in seconds of arc) and the position angle NAC. When the distance AC is comparatively large, say, over 2″, the two components may be photographed and the measures of distance and position angle obtained in the usual way, provided the range in magnitude of the two stars is not too great. But for the close doubles photography is out of the

question, for the images of the two stars could hardly be obtained distinctly separated. It is only in recent years that photography has begun to play a part in this branch of astronomy. The great majority of observations still continue to be made visually with the aid of a subsidiary instrument, attached to the eye-end of the telescope, called the filar micrometer. It consists of a circular plate, graduated from 0° to 360°, with an eye-piece mounted in the centre. In the focal plane are two parallel fixed "spider-wires" AB and CD (Figure 84). The plate is rotated until, as in the diagram, these wires are parallel to the direction in which the primary and component lie. Thus the position angle is measured. Also, there is a fixed wire EF and a movable wire GH, both at right angles to AB and CD. The distance between the primary and component is measured by getting the primary on EF and moving the wire GH until the component lies on it as in the figure. The distance is measured in terms of a micrometer scale, to which GH is connected, and thereafter converted into seconds of arc by means of the known characteristics of the instrument.

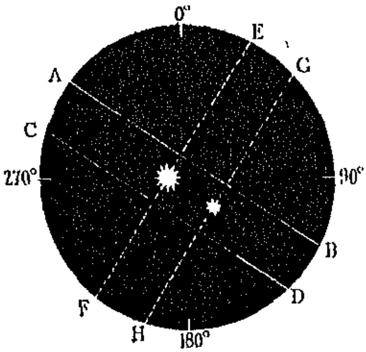
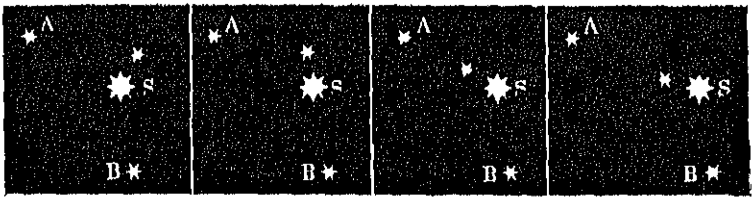


FIG. 84.

Herschel's observations showed, as has been said, that for several double stars, the companion was in orbital motion round the primary. For such a double star, we can represent diagrammatically a series of observations spread over a number of years. Figure 85 represents four such observations of a double star (S); A and B are two stars in the field of view of the telescope serving as reference points. The figure indicates the revolution of the companion around the primary. If the observations are carried out in this simple way, the period of the orbital motion of the component around the primary can be obtained. The shortest period of a double star found from visual observations of this nature is 5·7 years, and there are about 60 stars with periods less than a century; several hundreds have described a considerable part of their orbits

since their discovery, while many more have shown that their periods must be measured in hundreds and in thousands of years.

The measures of distance and position angle enable us to




1 2 3 4

Fig. 85.

plot the visible orbit of the companion around the primary. Figure 86 illustrates the observed orbit of the faint companion of Sirius around the latter. In every instance, the orbit is found to be an ellipse and, without going into the details of the

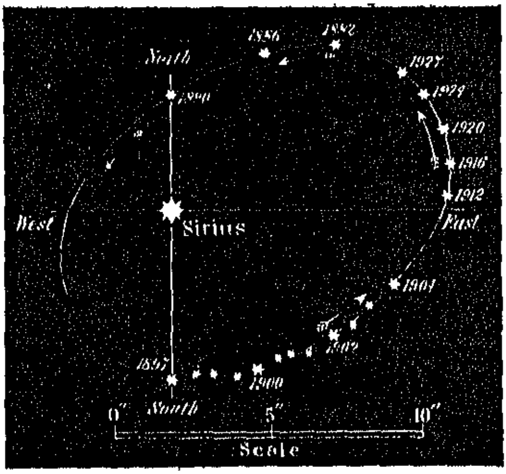



Fig. 86.—Orbit of Companion of Sirius.

argument, it is inferred that the orbital motion is the result of the mutual gravitation of the two stars forming the double. The primary and component are thus in close association, each a member of a physical system like the earth and moon. Optical doubles, on the other hand, owe the close proximity of

their components in the field of view of the telescope to their accidental positions in space in the same way that a castle and a distant mountain peak may from a particular view-point be almost in the same line of vision. Optical doubles are therefore of little interest in the present connection, and are excluded from the physically connected systems to which we apply the name double stars or binary stars.

Brief reference may be made here to a second test of the definite association of one star with another. We have seen in Chapter IX that near Capella there is a faint star with practically the same large proper motion of the former. These two stars are evidently journeying through space in company, but the orbital motion is so small that the period must be measured in thousands of years, and for this reason it is very difficult of detection. Common proper motion is to be regarded as a definite indication of the association of one star with another.

The importance of the careful observation of double star orbits, appreciated clearly by the early observers, lies in this: if the distance of the double star system is known, then from the details pertaining to the orbit it is possible to calculate the sum of the masses of the primary and component in terms of the sun's mass as unit and, in particular instances, the mass of each component separately. Knowledge of stellar masses, derived in this way, leads to very important conclusions which we shall examine in a later chapter. The enormous number of double star observations made, since Herschel's day, with such skill and patience by a great number of distinguished astronomers, can thus be utilised—if not now, then at some future time when the characteristics of the orbital motions may become more clearly defined—in revealing the masses of the stars. It is not possible here to mention the names of all the astronomers who have contributed to the discovery and observations of double stars; a century's work is summarised in the great catalogue of Burnham, published in 1906, which gives the relevant details concerning no fewer than 13,665 double stars (a small proportion of which are now known to be merely optical doubles). A new catalogue embodying more recent discoveries is now in preparation by Dr R. G. Aitken of Lick Observatory, who is one of the authorities in this branch of

astronomy. The great refractor recently set up by Dr Innes at Johannesburg will be devoted almost exclusively to double star observations in the southern hemisphere with every prospect of achieving valuable results. The whole sky, in fact, is being combed in the most thorough fashion for the detection and subsequent study of double stars.

Let us now see more precisely how the examination of the binary star orbits (an example of which is shown in Figure 86) can furnish the information so valuable in our study of the stars. We shall suppose that the observations fix the ellipse in which the companion appears to us to revolve around the primary. A moment's reflection will show that the observed ellipse as illustrated in Figure 86 is not necessarily a small scale plan of the true ellipse which is described by the companion around the primary, for we cannot assume in general that the actual orbital plane is at right angles to the line of sight. If we place a circular sheet of paper on the floor at some distance away, it will appear to be oval in outline, and only if we are vertically above it will it appear truly circular. So it is with the observed orbit, or apparent orbit, as it is called. We require then to deduce from the apparent orbit the essential characteristics of the true ellipse in which the component revolves around the primary. The chief characteristics which we shall mention here are (i.) the eccentricity of the ellipse, (ii.) the inclination of the true orbital plane to the plane at right angles to the line of sight, (iii.) the semi-major axis of the true orbit. As the distance of the companion from the primary has been measured in seconds of arc, the semi-major axis is expressed in terms of the same unit. Now, if we know the distance of the double star from us, we can convert the angular measure of the semi-major axis into miles or, as is usual, into astronomical units. Let us consider a specific example, namely, the double star system of Sirius. The distance of Sirius is known to be 9 light-years or $2\frac{3}{4}$ parsecs; the semi-major axis of the true orbit is a trifle over $7\frac{1}{2}$ seconds of arc; a simple calculation shows that the semi-major axis of the orbit of the faint companion around Sirius is a little over 20 astronomical units. Uranus moves around the sun in a great orbit of radius approximately 19 astronomical units. The semi-major axis of the orbit of the companion of Sirius is thus just a little

greater than the average distance of Uranus from the sun. But there is one difference between the two orbits. The orbit of Uranus is nearly circular, whereas the double star orbit is elongated owing to the high eccentricity. Figure 87 gives an accurate representation of the true orbit. When nearest Sirius, the companion is but 8 astronomical units away from the primary (somewhat nearer than Saturn is to the sun), while at its greatest distance from Sirius, the companion is 32 astronomical units away (a little more than the distance of Neptune, the most distant planet from the sun). It may be added that the companion of Sirius is not like the planets which shine by the reflected light of the sun, but is, like Sirius itself, a self-luminous star.

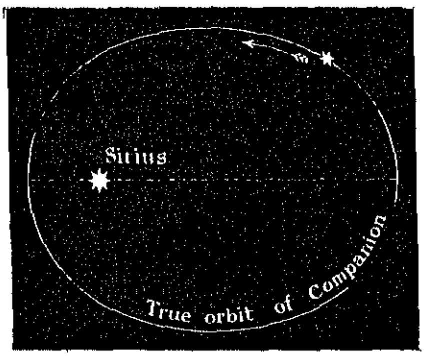



Fig. 87.

But the most valuable information obtained from the true orbit is the mass of the system in terms of the sun's mass as unit. The stars can be weighed, as it were, in an astronomical balance. The Newtonian law of gravitation is the basis on which the calculation is made. We have seen in an earlier chapter how Kepler's third law (as modified by Newton) can be applied to determine the mass of a planet (which is accompanied by one or more satellites) when the satellite's distance from the planet and its period of revolution around the planet are known. More accurately stated, the law gives the sum of the masses of the planet and the satellite, but as the mass of the latter is generally very minute compared with the mass of the former, the essential result is a sufficiently accurate estimate of the planet's mass in terms of the solar mass. But in double star systems, we are dealing with two bodies of comparable characteristics, so that there is no *a priori* reason for assuming that the mass of the companion is negligible compared with the mass of the primary; consequently the application of the law leads to the sum of the masses of the primary and companion—

in other words, to the total mass of the system. One other essential for the calculation is necessary, namely, the period of revolution. When this is known, the mass of the system is found. In the case of Sirius, the revolution period is known accurately; it is 50 years. The calculation shows that the mass of Sirius *plus* the mass of the companion is 3·4 times the mass of the sun. In the foregoing explanation it has been assumed that we have been dealing with double star systems for which complete orbits are known. But when observations have followed the companion through a part of the orbit, it is possible—if the observations are sufficiently accurate—to deduce the elements of the orbit, including the period and the semi-major axis, and so to calculate the mass of the system. The surprising fact emerges from the study of binary star orbits that the masses of the stars differ very little from the mass of the sun. Of the 22 visual orbits with periods less than a century, the masses of the systems vary from eleven times the sun's mass to a little less than a half of the sun's mass. If for the moment we attribute half the mass of a system to each of its component members, the range of the masses of single stars is from about 5 or 6 times the sun's mass to about one-quarter of the sun's mass.

To determine the individual masses of the primary and companion, some additional principle must be applied. In several instances, the proper motion of the primary has been found to be variable—in particular, we have seen in Chapter IX that the regular variation in the proper motion of Sirius led Bessel to the conclusion that Sirius was really a double star. The principle depends simply on this: it is the centre of gravity of a double star that moves with uniform proper motion, and that the observed proper motion of the primary, for example, is a combination of this uniform motion and of the effect of orbital motion around the common centre of gravity. The deviation of the motion of Sirius from uniform motion can then be made to give the ratio of the mass of Sirius to the mass of the double star system, and as the latter is known, we arrive finally at the mass of Sirius and the mass of its companion. In this way, the masses of individual stars have, in many cases, been accurately obtained.

If we consider only the binary stars whose distances are

known with considerable accuracy (it is to be remembered that the knowledge of distance is a pre-requisite to the calculation of mass), then for nearly a score of systems the masses of the individual stars range from roughly 5 times the sun's mass to a little less than one-fifth of the sun's mass; the latter is the smallest stellar mass so far measured (it refers to the fainter component of the faint double star Krüger 60).

The evidence from the visual binary stars is conclusive in this respect, that there is very little difference between one star and another as regards the amount of matter of which they are built. This is all the more surprising when the differences in their intrinsic brightness are considered; one star may be 10,000 times more luminous than another, and yet but ten or twenty times more massive. The study of the double stars leads also to this conclusion, that the more luminous a star is, the greater is its mass. The intrinsic brightness of a star and its mass are thus associated in some definite way; in a later chapter this relation between mass and luminosity will be discussed at greater length.

We have just seen how Kepler's third law has been applied to the solution of the problem, which may be re-stated thus: given (from observations) the semi-major axis (measured in seconds of arc) of a double star orbit, the period of revolution, and the distance of the double star from us, calculate the mass of the system. Now many of the double stars which show orbital motion are at such great distances that the measurement of their parallaxes by the usual trigonometrical method becomes one of considerable uncertainty, and consequently the calculation of the mass of these systems could have but little value. It appears at first sight that we neither know the distance nor can we calculate the mass of such a double star system. But supposing that we knew the mass, together with the semi-major axis and the period, Kepler's third law could clearly be used to enable us to calculate the distance of the double star; for the law would yield the semi-major axis measured in astronomical units which, combined with the angular measure obtained from the study of the orbit, would finally yield the distance of the system. We do not of course know the mass of the system accurately, but we can make a good guess. Let our guess be "twice the mass of the sun." As just indicated we can now

calculate the distance of the double star. Our guess is not likely to be far wrong, for as we have seen, stellar masses do not vary very greatly. Suppose that our guess is eight times too small, and that the mass of the double star should really have been 16 times the mass of the sun. When we have repeated the calculation for the distance we find the answer in the second case—expressed in parsecs or light-years—is just double the answer in the first case. It thus appears that a large error in the value assigned to the mass produces a much less proportionate error in the distance. We have taken almost an extreme case; in the majority of instances for which we assume the mass of the system to be twice the solar mass, the results for the calculated distances will be much more reliable, and at the worst they will be of much the same order of accuracy as for the more distant stars whose parallaxes are measured in the straightforward manner explained in Chapter XI. The parallaxes of the stars computed in this way are known as *dynamical parallaxes.*

One feature common to all visual binary star orbits must be mentioned in a sentence. It is the high values of the eccentricity, thus indicating greatly elongated orbits; an example we have illustrated in Figure 87.

Of all the naked-eye stars, one in every nine—a high proportion—is a visual binary. When we include the other classes of double stars which will be described immediately, the proportion becomes about one in three.

In 1889 the late Professor E. C. Pickering discovered the first of a new class of double stars. He noticed that the spectrum lines of the brighter component of the double star Mizar, in the Great Bear—the first visual double star to be discovered—were sometimes double, at other times single, and that the separation of the double lines increased and decreased in a regular period (*see* Plate XIV (*c*) which shows the doubling of the spectrum lines of Mizar). The explanation of the phenomenon was that the bright component of Mizar was itself a double star; such a double star is known as a *spectroscopic binary.* Figure 88 illustrates how the sequence of changes observed in the spectrum arise. Consider a double star each component of which describes an elliptic orbit around the common centre of gravity at G. We shall take as a simple case a system such that the direction of the sun from the binary lies in

the orbital plane. The system as a whole will, in general, be moving relatively to the sun; let us ignore this for a moment and assume simply that the system is at rest relatively to the sun. By the principles of dynamics, this is equivalent to the statement that the centre of gravity G is at rest relatively to the sun. Consider now the first component. At a particular instant it is at A in its orbit when, according to the diagram, its orbital velocity is directed towards the sun. The lines of the spectrum of this component will therefore be displaced towards the violet; by measuring the displacement (in relation to the lines of the comparison spectrum), the actual velocity in the line of sight, at this particular instant, of the first component can be calculated. But at this instant the second component is at X moving away from the sun. The lines of its spectrum will consequently be displaced towards the red end of the spectrum; the velocity away from the sun can then be deduced. Hence, if each component is sufficiently bright to register its own lines on the photographic plate, the spectrum will show all the hydrogen lines, for example, as double. Suppose that some time later the first component is at B in its orbit; it is then moving across the line of sight and the spectrum lines will not be displaced. Similarly, at this moment, the second component is at Y, also moving across the line of sight. The hydrogen lines common to each star will be superimposed and will therefore appear as single lines. Sometime later, the components will be at C and Z respectively when the respective orbital velocities are inclined at an angle to the line of sight. But the diagram shows that at C the first component is moving partly away from the sun, and, partly, across the line of sight, so that its spectrum lines will be displaced towards the red; while the second component at Z will have its spectrum lines displaced towards the violet. By making

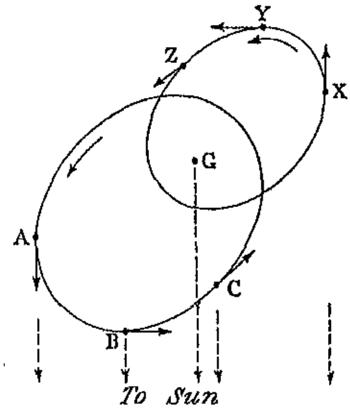


FIG. 88.

a series of observations in this way, the velocity of each component at different points of their respective orbits can be obtained. The observations give also the period of revolution, which is clearly the same for both components. If we now remove the restriction that the system is at rest relatively to the sun, then on account of the radial velocity of the system, the spectrum lines will show an additional and constant displacement towards the red or towards the violet, according as the system is receding from or approaching us. From the complete set of observations, velocity curves are drawn for

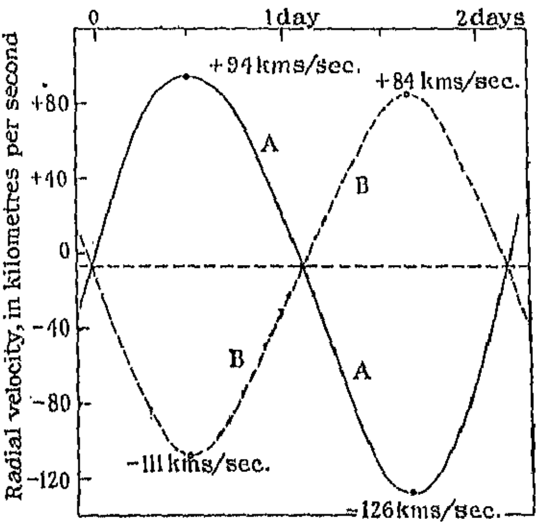



FIG. 89.

each component. Figure 89 illustrates the actual results obtained by Mr R. F. Sanford at the Mount Wilson Observatory for the spectroscopic binary known as "Boss 4247." The period of this binary is 2·3 days and the curves represent the radial velocities of the two components throughout a period. The diagram shows that for component A the velocity as given by the spectrum lines fluctuates in a regular way between +94 kilometres per second (this is a velocity of recession) and −126 kilometres per second (this is a velocity of approach), and that for component B the velocities range between +84 and −111 kilometres per second. A further deduction from the

observations is that the system as a whole is approaching us with a velocity of 12½ kilometres per second.

Rather less than 20 per cent. of spectroscopic binaries are such as to give the characteristic spectrum lines of *both* components. When one component is much fainter than the other, only one set of lines is registered photographically, so that only one velocity curve can be drawn.

Let us now consider what can be deduced from the velocity curves, an example of which is shown in Figure 89. If the direction of the sun actually lay in the plane of the orbits, as we assumed in Figure 88, Kepler's third law would enable us to find the individual masses (expressed in terms of the sun's mass) of the components and also the semi-major axes of the orbits. But in general the plane of the orbits will be inclined at an angle to the line of sight and the velocity curves are unable to furnish the details. All that we can deduce for a spectroscopic binary is the exact ratio of the masses of the components, together with the least value of the semi-major axes of the orbits. For the star "Boss 4247," it is found that the ratio of the masses is 1·1 to 1, that the stars must be at least 1·1 and 1·0 times as massive as the sun, and that the average distance of one component from the other must be at least 6,500,000 kilometres or about 4 million miles. When only one component is sufficiently bright to be photographed, the information to be deduced is very much more incomplete.

Of the spectroscopic binaries discovered (their number is well over a thousand), a little more than half have periods less than 10 days, a quarter have periods between 10 and 100 days, and for the remainder, the periods exceed 100 days. The shortest period is 8 hours and the longest 15 years. The star with this latter period is also a visual binary and our information with regard to this system is unusually complete. Let us see what a period of 8 hours really signifies. If we assume various values for the sum of the masses of the components, we can calculate by Kepler's third law the corresponding average distances between the components. For example, if we take the mass of the particular system, for which the period is 8 hours, to be 8 times the sun's mass, the average distance between the components of the stars comes out to be 1¾ million miles. We know that the sun's diameter is 865,000 miles, and there is no

reason to suppose that the diameters of the components of spectroscopic binaries are much less than this figure. Our calculation thus leads to the picture of two stars almost in contact, revolving about their common centre of gravity; and no alteration in the assumed sum of the mass of the system (consistent with ascertained facts regarding stellar masses) will seriously affect the picture. At the other extreme, we have the widely separated visual binaries revolving in mighty orbits many times greater than the orbit of Neptune. The separation of double stars into the two classes, visual binaries and spectroscopic binaries, is an artificial separation conditioned by the limited powers of our observing devices; the two components of a spectroscopic binary are too near each other to be seen separately even in a powerful telescope, and the changes in the orbital motions associated with a visual binary are generally too small to be measured by the spectroscope.

We have seen that the eccentricities of the visual binary orbits are high; for spectroscopic binaries, on the other hand, the eccentricities are small. When the periods of the latter are small—that is, when the components are very close together—the orbits are nearly circular. There is undoubtedly a close relation between length of period and the values of the eccentricities.

Although the observations of any particular spectroscopic binary can only tell us that the masses of the components must not be smaller than certain values—owing to our ignorance of how the orbital plane is inclined to the line of sight—yet by grouping together all the results for stars of a certain spectral type and calculating what the average effect of the unknown inclinations will be, it is possible to arrive at results of great value. The following table shows the relation between spectral type and the average masses calculated in this way.

| Spectral Class. | Mass (Sun's mass as unit). |
|---|---|
| B0 to B2 . . . . | 20 |
| B3 to B5 . . . . | 8 |
| B6 to A3 . . . . | 4 |
| A4 to F4 . . . . | 2½ |
| F4 to G5 . . . . | 2 |

The remarkable fact which this table elicits is the steady decrease of the stellar masses corresponding to the decrease of

stellar temperature. According to the table the hottest stars (B0 to B2) are the most massive. Here again is a fact, well-established and definite, evidently the consequence of some general law of nature; once more we postpone discussion of what the information concentrated in the preceding table implies.

Up to near the middle of 1927 the most massive star discovered is "Plaskett's Star"—a spectroscopic binary whose components are at least 75 and 63 times more massive than the sun. The spectral class is O8 and, as we have seen in an earlier chapter, stars of this class are notable for their remarkably high temperatures. If Mr Otto Struve's results of 1927 are confirmed, Plaskett's star will have to yield pride of place to a recent discovery. Struve's star—it is believed—consists of four components A, B, C and D. The lines due to A and C are visible in the spectrum. A and B form a close spectroscopic binary with a period of 121 days and C and D form also a close spectroscopic binary with a period of about 8 days. The close binaries are themselves components of a more open spectroscopic system with a period of $3\frac{1}{8}$ years. The total mass of this quadruple system is calculated from the velocity curves to be not less than 950 times the solar mass.

We consider now a third class of double stars known as *eclipsing binaries*. In 1783 Goodricke of York announced that the brightness of the prominent star Algol in the constellation of Perseus fluctuated in a definite and periodic manner. The character of the light changes is best described in terms of apparent magnitude. In an earlier chapter it was seen how the apparent magnitudes of the stars can be measured. We shall then suppose that the apparent magnitude of Algol is measured at frequent intervals by the accurate methods at the disposal of astronomers, amongst which may be mentioned the photo-electric method referred to on page 151. The changes in the apparent magnitude of Algol occur in a period of 2 days 20 hours 49 minutes; for about 2 days and 11 hours Algol is of magnitude 2·3, then for 5 hours it gradually decreases in brightness to magnitude 3·5, then gradually for 5 hours increasing in brightness to magnitude 2·3 again. The changes in magnitude throughout a period are conveniently depicted by means of a *light curve*; Figure 90 illustrates the light curve actually found

for Algol. The modern observations made with a photo-electric equipment show that there is also a slight decrease in brightness about a day and a half after the star has reached its faintest magnitude. The two dips in the curve are called the principal minimum and the secondary minimum. Goodricke suggested that the variation in the light of Algol was due to the periodical

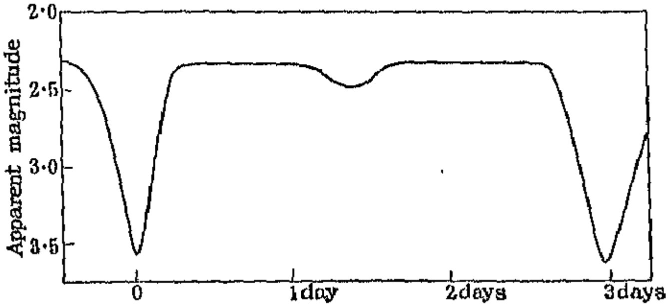



FIG. 90.—LIGHT CURVE OF ALGOL.

eclipse of the star by a less bright companion, that, in fact, Algol was a double star. One condition for an eclipse of this nature is that the direction in which we see the star must be in or near the plane of the companion's orbit around its primary. Figure 91 illustrates the circumstances attending the light variation in an eclipsing binary. The companion is shown at several points A, B, C and D in its orbit around the primary. At A, for

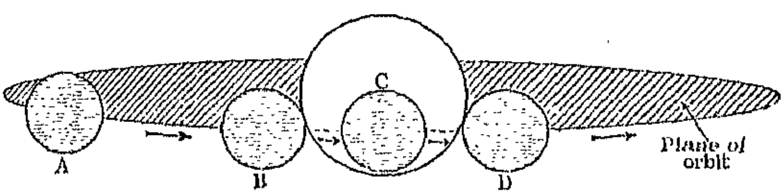



FIG. 91.

example, the light which we receive from the system is the light from the primary plus the light from the companion: at C, the companion partially eclipses the primary and the total light from the system is thus much less than in the former case. At B, the companion is just about to eclipse the primary; and at D, the eclipse is just over. Thus in the interval represented by the time taken by the companion to go from B to D, the light of

the system gradually diminishes as the eclipse begins, then gradually increases as the eclipse ends; in the light curve, this corresponds to the principal minimum. In the same way, it may be seen that the companion will be hidden for a time behind the primary, but as the latter is much brighter than the former, the loss of light is not so conspicuous; this corresponds to the secondary minimum.

The conjecture that the variation in the light of such stars as Algol is due to the periodical eclipsing of one star by another, as represented in Figure 91, has been amply verified by spectroscopic observations, for the spectrum lines of such stars as can be observed by the spectroscopic method show the characteristic periodic displacements typical of the spectroscopic binary.

Let us now consider the principal information afforded by a study of the light curve of a star such as Algol. Firstly, the sizes of the stars, measured in terms of their average distance apart as the unit, are obtained; in other words, we have the information with which we can construct a model of the system. The spectroscopic observations when available come to our aid in telling us what the scale of the model really is, and consequently we can calculate the actual sizes of the members of the binary system. Secondly, the light curve tells us the eccentricity of the orbit—for eclipsing binaries, as for spectroscopic binaries, the orbits generally have small eccentricities, so that they are nearly circular—and also the relative brightness of the two components. There are certain other refinements in the deductions from the light curve, only one of which will be mentioned here. For a very close binary, with the two components revolving almost in contact, the gravitational attraction of one component on the other will produce a tidal effect on a large scale. The stars can be regarded no longer as spherical but as ellipsoidal, each very much like a rugby football or an airship. The light curve can predict the shapes of the components as well as their relative sizes.

But the most valuable and interesting information is that relating to the sizes and densities of the components of those eclipsing binaries which can be observed also as spectroscopic double stars. It is found that the diameters of these stars are generally from two to five times the solar diameter—that is to say, from about 1½ to 4 million miles. The sun is but a pigmy

compared with the voluminous members of such eclipsing binaries. The light curve in conjunction with the spectroscopic observations can give the masses of the components; the volumes of the stars can be calculated readily from the known diameters, and consequently the average densities of these stars can be deduced. There is a significant increase in density as we go from B type stars to F type stars, as shown below (the density is expressed in terms of the sun's density as the unit).

| Spectral Class. | Density. |
|---|---|
| B0 to B3 . . . . | 1/25 |
| B5 to B8 . . . . | 1/12 |
| B9 to A3 . . . . | 1/7 |
| A5 to F2 . . . . | 2/5 |

If we imagine our own sun swollen out to three times its present

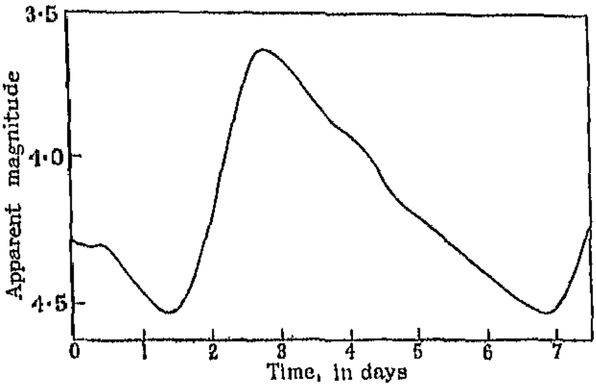



FIG. 92.—LIGHT CURVE OF δ CEPHEI.

diameter, its density would be roughly that of the earlier B class stars in the first line of the preceding table.

Eclipsing binaries belong to one class of variable stars. We consider now another class, known as the *Cepheid variables*, so called after a typical member of the class in the constellation of Cepheus. The light curve of this star is shown in Figure 92. It will be seen that the star when brightest is about magnitude 3·7 and when faintest about magnitude 4·5. The period is a little less than $5\frac{3}{8}$ days. Cepheids with periods less than 1 day are sometimes designated Cluster variables—as their name suggests, these stars are generally found in star clusters. At

first sight it might be presumed that the light curve is the evidence of the binary nature of such stars, that, in fact, Cepheids are but eclipsing variables. But several circumstances negative such an assumption. The most telling argument is this. If a Cepheid's light curve is analysed as for an eclipsing binary, the model of the system which is thus deduced shows that one component must be partly inside the other! For such and other reasons we must seek a different explanation of the variability of the light of these stars.

Some years ago Miss Leavitt of Harvard Observatory discovered a remarkable relation between the periods of light variation and the intrinsic brightness of Cepheid variables in the Lesser Magellanic Cloud—a prominent star cloud in the southern sky. From a series of photographs the periods of these variables, ranging from about 15 hours to 125 days, were obtained. Also from the photographs, the photographic magnitudes of each Cepheid throughout its light-period were obtained; in particular, the average magnitude throughout the period of light variation was found. The average magnitudes of the individual stars ranged from about the 12th to the 17th magnitude. For the faintest stars the periods were smallest, and for the brightest stars the periods were greatest; for all the variables examined there was a definite relation between the period of light variation and the average magnitude of the stars concerned. Now the star clouds are so far away that all these variables may be assumed, for practical purposes, to be at the same distance from us; consequently, the magnitude measures give us a reliable picture of their relative brightness. Thus we can say that a 12th magnitude variable is 100 times more luminous than one of the 17th magnitude. If only the distance of the clouds were known, the average apparent magnitude as deduced from the photographs could be converted into absolute magnitudes—that is, the magnitudes which the stars would have, if they are all supposed at a distance of 10 parsecs or 33 light years from us. Miss Leavitt's results would then enable us to say that a Cepheid with a period, say, of ten days was of a certain absolute magnitude. Further, if this characteristic inter-dependence of absolute magnitude and period holds wherever in the universe Cepheid variables are to be found, the distances of these stars can easily be obtained.

Let us take an example. On the scale of absolute magnitude a Cepheid with a light period of ten days is believed to be of absolute magnitude $-3$. If its apparent magnitude is found by the usual methods to be 17, its actual distance must be 10,000 times the distance to which the absolute magnitude corresponds, that is, 10 parsecs. We must infer, then, that the star is at a distance of 100,000 parsecs or 326,000 light-years. Here then is a powerful method of throwing the fathom-line into the outermost regions of space, and we shall see later the results in the case of the star clusters and spiral nebulæ. But there is one link in the chain that has still to be forged; we require to know the actual distance of at least one Cepheid before we can connect definitely the periods of light variation with the corresponding values of the absolute magnitude. Dr Shapley has succeeded in doing this for several of the bright Cepheids. The relation between the period and absolute magnitude is thus established; it is illustrated in Figure 93. From the curve, the absolute magnitude of any Cepheid whose period is known can be derived at once. For example, if the period of light variation is 4 days, the curve shows that the absolute magnitude of the Cepheid is $-1{\cdot}8$; if its average apparent magnitude is measured in the usual way, its distance in parsecs or light-years may then be calculated.

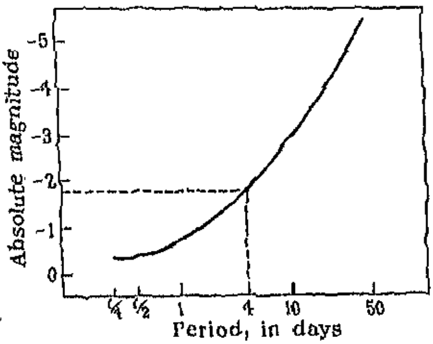



Fig. 93.

What then is the nature of a Cepheid? In 1914 Dr Shapley suggested that many of the observed facts could be suitably explained in terms of a pulsating star. This is the pulsation theory developed mathematically at a later date by Professor Eddington. The star is supposed alternately to expand and then to contract, the complete period of volume changes being the period of light variation. This theory explains, for example, the observed changes in radial velocity and the changes in spectrum, for the character of the spectrum lines depends on

the physical conditions in the star's atmospherical regions; expansion of a gas implies a decrease of pressure and temperature, whilst contraction implies increase of pressure and increase of temperature. Although the pulsation theory explains many of the facts, it has not yet achieved complete success. The rival theory is that propounded by Sir J. H. Jeans. The Cepheid is imagined to be an ellipsoidal star in rapid rotation about its smallest diameter as axis and subject to oscillations; the star, in fact, is imagined to be on the point of breaking up into two stars. The Cepheid stage is then, according to Jeans, antecedent to the close binary stage in which many of the spectroscopic binaries undoubtedly are. Here again, theory is partially successful in explaining several of the phenomena observed. But the interesting problem of Cepheid variation still awaits a complete solution; essentially it is a mathematical problem of very great complexity and difficulty.

The two classes of variable stars which we have just described—the Algol variables (or eclipsing binaries) and the Cepheid variables—are characterised by the regularity with which one sequence of changes is exactly reproduced in successive periods. When once the light curve is known, the circumstances of the star's light can be accurately predicted for any future time. We now consider three classes of variables in which this regularity is almost wholly or completely absent; they are the long-period variables, the irregular variables and the novæ (or new stars). The best known member of the long-period variables is the star known as Mira or "the Wonderful" in the constellation of Cetus (the Whale). Its period, on the average, is almost 330 days, but it may be several days longer or shorter. At maximum, it is on the average about the third apparent magnitude; sometimes at maximum it may be as bright as magnitude 1·5 (it is then a very conspicuous object in the sky), while at other maxima it may be as faint as the fifth magnitude. The minima are similarly erratic, generally between magnitudes 8 and 10. The variability of Mira was detected as early as 1596. To the naked eye, the phenomenon is very striking; from being a conspicuous object in the sky, the star gradually fades away until some three months later it is invisible to the naked eye, remaining invisible for some five months, after which it gradually comes into view again.

There are several hundreds of similar stars known, most of them with average periods of about a year. These stars belong in the great majority of instances to spectral class M, the remainder being classified as type N, R, or S. In all cases they are red stars. The spectrum undergoes remarkable alterations throughout the light period, and the radial velocity is also subject to periodic changes. It is possible that the observed changes may be interpreted in terms of an irregular pulsation but, at present, the long-period variables present a problem which can only be solved after much more patient investigation.

There is very little known about the irregular variables. The changes in their light appear entirely capricious. For a year or two, a star of this class may show no sign of light variation and then, without warning, it may fade away by a magnitude or two. The erratic behaviour of such a star might conceivably be explained by the partial and varying obscuration of the star, in its journey through space, by chance clouds of gas or dust particles lying between us and the star in interstellar space.

The class of stars known as *Novæ* or "new" stars or temporary stars is characterised by the startling rapidity with which an insignificant star suddenly flares up—almost with the suddenness of an explosion—into a prominent and occasionally a most conspicuous object in the sky. Its grandeur, however, is but short-lived, for it soon fades away to insignificance. The first historical nova was that of 134 B.C., which is said to have impressed the famous astronomer Hipparchus with the desirability of cataloguing the visible stars. On November 7, 1572, a nova—generally known since as Tycho Brahe's nova—was discovered which in a day or two surpassed in brilliance every star in the heavens; in fact, its brightness was so great that it was easily visible in broad daylight. In sixteen months it had faded away out of sight. Kepler's nova—discovered in 1604—was at one time as bright as Jupiter, and it remained visible to the naked eye for about a year. Between 1500 and 1901, no fewer than 16 novæ have been recorded. Modern photographical methods are now responsible for yearly accessions to the numbers of discoveries, many of them in the remote depths of space. To illustrate the light changes accompanying the outburst and subsequent life of a nova, two instances will be

described in greater detail. On February 21, 1901, Dr Anderson of Edinburgh discovered a new star in the constellation of Perseus, known now as Nova Persei; it was then of magnitude 2·7. From photographs taken of that part of the sky some 27 hours earlier, it was clear that the star could not have been then brighter than the eleventh magnitude; 38 hours after discovery the star reached its pinnacle of brightness and it was then as bright as Capella, the brightest star in the northern heavens. It then began to fade away—not regularly, for it would sometimes brighten up, temporarily, by quite appreciable amounts. Sir Robert Ball used to relate, in his own inimitable way, how when the nova was near the limit of naked-eye vision he had taken a party out into the open to show them the new star, only to find that it had disappeared. Next night, he took out another party "to show them the disappearance, but—there it was again!" The nova is still a faint telescopic object, not quite constant in brightness.

Nova Aquilæ was discovered by Dr W. J. Luyten at Utrecht on June 6, 1918, while engaged in making a drawing of the Milky Way. It was then of magnitude 5·8. Two days later it was as bright as a first magnitude star, and on June 9 it had become the brightest star in the northern sky and almost as bright as Sirius. Thereafter, its brightness decreased as in the case of Nova Persei.

The distances of several novæ have been measured; the results indicate that the outbursts must have taken place several hundreds of years before the tidings, carried with the velocity of light, reached the earth.

Sir William Huggins was the first to examine spectroscopically the light of a nova. It is hardly possible here to describe the rapid and complicated changes in the spectrum of a nova which even yet are not completely understood. It will perhaps be sufficient to mention two things. When the star is brightening, its spectrum has the characteristics of a B or A class star; long after the outburst, it has passed into type O. Again, during its bright stages, the spectrum lines show a great displacement towards the violet end of the spectrum, indicating a velocity of approach, as in the case of Nova Aquilæ, of about 1200 to 1500 miles per second. The interpretation of this stupendous velocity seems to be that the star is

expanding under the violent stimulus of something akin to an explosion.

What is the cause of this celestial outburst which shatters the equilibrium of a commonplace and sedately behaved star? Novæ nearly always occur in the Milky Way where the stars are most numerous and where there is an abundance of nebulosity; by inference, an external agency is postulated. There is the suggestion that the celestial catastrophe is the result of the collision or near approach of two stars; the suggestion that it is due to the rushing of the star through a gaseous cloud in the same way that a meteor attains such brilliancy in its passage through our atmosphere; the suggestion that part of the immense energy imprisoned within a star is suddenly released by the surface penetration of a body that may be no bigger than a minor planet or satellite. Whatever the cause, the following circumstances (with which we conclude the chapter) relating to Nova Persei (1901) may be significant to the future elucidation of the problem. Some months after the outburst, long exposure photographs revealed the presence of a faint nebulosity in the neighbourhood of the star. Moreover, successive plates showed that this nebulosity appeared to be moving outward from the star, at an angular rate that could be measured. On any reasonable estimate of the distance of the star, the actual outward propulsion of matter could hardly be entertained as a serious proposition, for the velocity in miles per hour was of a magnitude unprecedented in astronomy. There was only one possible meaning. Nova Persei was surrounded by nebulosity extending to great distances from the star, and what was observed was not the outward motion of nebulosity, but the successive illumination of yet more distant parts of it, as the light of the outburst travelled radially outwards from the star. The significant fact is that one nova at least is known definitely to be situated, if not actually within a diffuse gaseous cloud, then in very close proximity to it.

# CHAPTER XV

## GIANT AND DWARF STARS—THE EVOLUTION OF THE STARS

THE chapters immediately preceding have been mainly concerned with the characteristics and properties of individual stars. The visual binaries provide the means of estimating stellar masses; the eclipsing binaries enable us to calculate the densities of these stars; the spectroscope arranges the stars in classes according to colour or surface temperature; and the measures of distances allow us to compare the absolute magnitudes of the stars. The properties of the stars which we shall consider in this chapter are: absolute magnitude (which is merely an index of luminosity), spectral class, mass and density.

Professor Hertzsprung, in 1905, was the first to realise fully the amazing diversity in the intrinsic brightness of the stars, and he coined the terms *giants* and *dwarfs* to express the distinction between stars of great brightness and stars of feeble light power. It was not, however, until 1913, when a more imposing amount of accurate information concerning stellar distances in particular was available, that the distinction between giant and dwarf stars was more fully realised. In that year, Professor H. N. Russell of Princeton assembled this patiently won information in the form of a diagram—known now as a "Russell diagram." In all, he had about 300 stars whose distances had been measured in the usual way and which had been placed in one or other of the spectral classes. To each star, then, could be attributed two characteristics, absolute magnitude and spectral type. In Figure 94 the spectral types are written along the top and bottom. Thus a star of spectral type Ko can be represented by a dot somewhere in the line joining the two K's—and intermediate types, e.g. K4, can be represented in the same way. If the absolute magnitude of the star is, for example, +10, it can be represented by a dot

vhere on the horizontal line through "+10" in the al scale. Thus a star of absolute magnitude +10 and ·al type Ko can be represented by a definite dot in the . This was done by Professor Russell for each of the tars. What he found was this: with remarkably few ·tions, the dots lay within the area, as shown in Figure 94, :d like a laterally inverted 7. Consider the red stars of ral classes K and M; the diagram shows that they are ed sharply into two distinctive groups. One group consists ırs of high luminosity—the representative dots are in the ontal area XY—of absolute magnitudes between −2 and

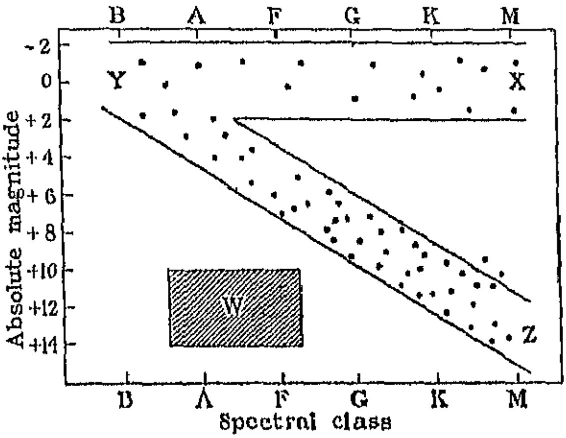



FIG. 94.—THE RUSSELL DIAGRAM.

; roughly, and the second group consists of the feebly luminous rs of absolute magnitude from about +8 to +14 (the repre- tative dots are towards the bottom of the sloping leg YZ). e first group are the giant stars of spectral class K and M; second group are the dwarf stars of these classes. Remem- ·ing that a difference of 5 magnitudes represent a ratio in ghtness of 100 to 1, we see that the diagram illustrates the :t that a giant M star, for example, is at least 10,000 times ore luminous than a dwarf of the same spectral class. At the ıer end of the spectral series—classes B and A— the diagram ows no sharp division—the stars are of absolute magnitudes 2 or brighter; they are all in fact giants. Professor Russell ıs hardly satisfied with the evidence furnished alone by the

stars whose parallaxes had been directly measured. Could the evidence be further strengthened from other sources? We have seen how the distances of the stars in the Taurus cluster were measured. The parallaxes of some 150 stars in this cluster and in three other similar clusters were available. The dynamical parallaxes of over 550 stars—derived from visual binary systems—were also pressed into service. Each group of stars gave rise to a distribution of dots in a Russell diagram in entire agreement with that derived from the 300 parallax stars. Since 1913 the number of measured parallaxes has been increased at least tenfold; but they only add further confirmation to the main features illustrated in Figure 94.

Let us examine the Russell diagram in greater detail. We have observed already that all the blue and white stars (classes B and A) are intrinsically bright and that the red stars are either highly luminous or intrinsically very faint. As regards the red stars, the feature just mentioned might, at first sight, be attributed to the method of selecting stars to be measured for parallax. These fall into two groups, as a rule; firstly, the bright naked-eye stars, a large percentage of which are stars of great luminosity; and, secondly, the faint red stars of large proper motion (as large proper motion is a fairly reliable index of nearness, these stars are really intrinsically very faint). Such a selection arbitrarily divides the red stars into two clearly defined groups of stars, one of high luminosity, the other of feeble luminosity. The older parallax programmes might have been open partially to a criticism of this sort but with a more comprehensive search of the heavens the significant fact remains that there is a clear gap of at least 6 magnitudes—on the Russell diagram—between the giant M stars and the dwarf M stars. In other words, no M type star has been found between absolute magnitude +2 and +8 roughly. The clear-cut cleavage between the giants and dwarfs of spectral class M must be regarded as an accepted fact. The same is true, in general, of the stars of classes K and G; for stars of class F the distinction between giants and dwarfs is not so fine, and for the A and B stars there is little or no division at all. Another point of interest in the diagram is that all giant stars are very much of the same intrinsic brightness, whatever their spectral class. The study of eclipsing binaries and the results of other investiga-

tions make a further contribution to the problem we are considering. On the average, the stars of class B are found to be about one-tenth as dense as the sun and the density rapidly diminishes for giant stars of succeeding type. Nor is this all, for the density increases on the main series—along the sloping leg YZ of the Russell diagram—from about 1/10 of the solar density for B stars, unity for the sun (a dwarf of type Go), and much higher densities for the succeeding classes K and M. Also, there was some evidence even in 1913 that stars intrinsically fainter than the sun are less massive and that the more luminous B type stars are at least several times more massive than the sun—but we had to wait till 1924 before light was thrown on this relationship between mass and luminosity.

The doctrines of evolution are familiar in the realm of biology. Is it possible that the stars change, with the passage of time, from one distinctive type to another? in other words, is there any evidence of stellar evolution? Change there must be, for every star is pouring forth vast quantities of heat and light energy, and every day and every year its store of energy is being depleted. Can we associate the different kinds of stars in the heavens with definite stages in the life-history of a typical star? Before 1913 it was generally believed that the spectral classes B, A, . . . M represented different chapters in a star's history; that a star was born with the high temperature associated with stars of class B, and as its store of energy was gradually dissipated by its radiation of heat and light, it passed through the successively cooler classes till it reached class M. Beyond class M lay final extinction as a luminous body. Sir Norman Lockyer was virtually alone in his disbelief of this idea of evolution. To him, the B type star represented the heyday of youth somewhere between the stellar birth and final extinction. In many respects, his ideas were very much like those put forward by Professor Russell in 1913, which we shall now describe.

The facts which enabled Russell to drop a bombshell on contemporary ideas are mainly summarised in the Russell diagram. Russell's theory (in 1913) of giants and dwarfs is as follows. A star begins its *visible* existence as a giant M star—a bloated globe of gas, many thousand times more tenuous than the air we breathe. Because of the loss of energy and of the

influence of gravitation, the globe contracts and as it contracts the temperature rises. The star then passes through the spectral series in the reverse order M to B until it reaches the stage denoted by class B. At this point, the density becomes so considerable that the increase of heat energy resulting from subsequent contraction is insufficient to balance the loss by radiation. The star then cools as well as contracts and passes down the main series B to M, eventually reaching the condition of a dwarf M star. Figure 95 is a diagrammatic illustration of the evolutionary course of a star on Russell's theory. The first part of a star's journey—that from class M to B in the giant stage—had been predicted in general terms by the mathematical researches of Homer Lane. The underlying assumption was that the star consists of what is known in Physics as a perfect gas to which the then known physical laws were applicable. When the density reached a certain critical value as the result of the continuous gravitational contraction, the further progress of the star could only be conjectured; this critical density was not known accurately, but it was believed to be about 1/10 that of water. Now this is not far from the average density of the B type stars. The Russell "Giant and Dwarf" theory of stellar evolution had an astonishing success in its explanation of the then known facts relating to the stars. For example, the giant stars of classes B to M were of much the same luminosity; this must be, because in passing from the M stage towards the B stage, the effect of the decrease in surface area, and therefore of the star's total luminosity, is approximately balanced by the greater brilliancy —due to the rise in temperature—of each square inch of its surface. Later discoveries only served to add greater weight to the theory. Amongst these we describe two.

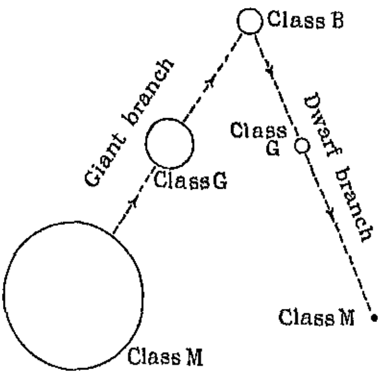



FIG 95.

Consider the K class stars. These are not all alike, for some are giants and some are dwarfs. The spectroscopist used

to class them indiscriminately as K stars, but are the spectra of the giants exactly similar to the spectra of the dwarfs? The very different physical conditions existing in the stellar atmospheres suggest that there ought to be differences. In the giants, the stellar material is in a very diffuse state—in other words, the gas pressure is very low—while in the dwarfs, the density is very considerable. Under the conditions of temperature and pressure in the dwarfs, the ionisation of the atoms of a particular element may hardly take place at all, whereas with the same temperature but with a greatly reduced pressure, as in the giants, the *ionisation* of the atoms may proceed to a much greater extent. For such an element, the lines due to the ionised atoms will be weak for the dwarf and strong for the giant, and the lines due to the neutral atoms will be strong for the dwarf and weak for the giant. Similar differences in the intensities of the other lines in the spectra of giants and dwarfs may be anticipated. The challenge thrown out to the spectroscopist was not long in bearing fruit. Dr Adams at Mt. Wilson detected such differences in the intensities of the lines of certain elements (and certain other differences too) in the spectra of giant and dwarf stars of the same spectral type. More than that, a new method of estimating the distances of the stars was developed with amazing success. The parallaxes so derived are known as *spectroscopic parallaxes.* The method is based first of all on stars of known parallax—and therefore of known absolute magnitude, both giants and dwarfs alike—and of the same spectral class. Consider a pair of lines A and B in the spectrum of a dwarf star in which A is shown up strongly and B weakly according to the principles just stated; in the spectrum of the giant the reverse is observed, namely, A is shown up as a weak line, B as a strong line. The numerical relations between the measured intensities of a pair of lines such as A and B are taken as a criterion of varying low luminosity in the several dwarf stars concerned and as a criterion of the varying high luminosity in the several giant stars concerned. These relations, it must be repeated, are derived from stars of known absolute magnitude. The process is then reversed. The spectrum of any other star of the same spectral type is examined; the relative intensities of a pair (or pairs) of the particular spectrum lines is measured; then from the empirical relation found between relative line-

intensity and absolute magnitude, the absolute magnitude of the star is deduced. The observed apparent magnitude then enables us, finally, to deduce the parallax.

This is indeed an astonishing achievement, that from a simple examination of a star's spectrum its absolute magnitude and hence its distance can be found. Already the parallaxes of several thousands of stars have been obtained within a very few years; in this respect, the contrast between the spectroscopic method and the slow and difficult trigonometrical method is very striking. But the basis of the former method is the accurate determination of parallaxes by the latter and so one of the chief concerns of practical astronomy to-day is a yet more strenuous prosecution of the older method. The new method has one striking advantage over the old. If the star's spectrum can be satisfactorily photographed, it does not matter whether the star is 10 or 10,000 parsecs away, for its distance can be deduced. In the trigonometrical method, on the other hand, stars with parallaxes less than $0''{\cdot}005$—that is to say, at distances greater than 200 parsecs—are near the limit of reliable measurement. For these reasons the greater power of the spectroscopic method is beyond dispute. It may be added that the spectroscopic parallaxes corroborate in general the separation of stars into giants and dwarfs as represented in the Russell diagram.

Professor Russell, as we have seen, attributed the immense disparity in luminosity between the giant M stars and the dwarf M stars to an immense disparity in volume. The similarity in spectrum was taken to indicate that a square inch of the surface of a giant star was of the same brightness as a square inch of the surface of a dwarf star, so that a 10,000 to 1 ratio in total luminosity, for example, would indicate an identical ratio in the surface areas of the two stars, and therefore a ratio of 100 to 1 in the stellar diameters. We have seen that the diameter of certain of the eclipsing binary stars can be calculated, but is there any means of verifying the stupendous bulk of the giant stars—especially those of class M—reached in the crude calculation just made? The answer is that it is comparatively easy to calculate the angular diameters of the stars—and in a few instances angular diameters have actually been measured, with results in harmony with the calculations; if the parallaxes

are known, the stellar diameters (in miles) can finally be calculated. Let us take a simple example. We know the angular diameter of one star very accurately. At the earth the sun's diameter subtends an angle of 32′. Suppose that there is a star—call it A, similar in every respect to our sun—at a distance of 10 parsecs. In round figures, the latter's diameter would subtend an angle of one-thousandth part of a second of arc. At this distance the star would be of apparent magnitude 5. Suppose further that there is a second star B, whose diameter is twice A's diameter, situated at a distance of 20 parsecs from us, and a third star C similar in every respect to A also at a distance of 20 parsecs. We suppose all three stars to be of the same spectral type as the sun, namely, Go. Now as the distance of C from us is twice that of A, the star A will appear to us to be four times brighter than C. Also since the diameter of B is

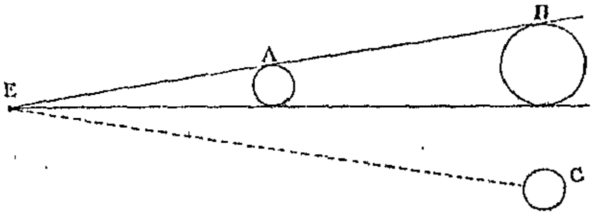



FIG. 96.

twice that of C, the surface area of B will be four times that of C; and as B and C are at the same distance, B will thus be four times brighter than C. We have seen that A is four times brighter than C; it follows that A and B will appear to us to be equally bright; in other words, their apparent magnitudes will be identical. But the relation between the distances and diameters of A and B means that the angles subtended at the earth must be the same. This is illustrated in Figure 96. Hence we arrive at a general result, viz. the angular diameters of stars of the same apparent magnitude and of the same spectral class are equal. Consider now Capella, a star of type Go and apparent magnitude 0·3. Its apparent brightness is thus about one hundred times that of our star A; consequently the angle subtended at the earth by Capella's diameter must be ten times that of A; that is to say, the angular diameter of Capella is one-hundredth part of a second of arc—the angle subtended by a

halfpenny placed 330 miles away. The parallax of Capella is 0″·06 (corresponding to a distance of about seventeen parsecs or about fifty-five light-years); making use of this, we arrive at the actual diameter of Capella, namely, about 15 million miles or approximately eighteen times the sun's diameter. The answer found from more accurate data than that we have used in this somewhat crude calculation is that Capella's diameter is about fourteen times that of the sun. In this simple calculation we have considered only stars of the same spectral type, but a moment's reflection will show that it can be extended to any spectral class, provided that we know the relative surface intensity of stars of different spectral classes. On these lines the angular diameters of many stars have been calculated by various astronomers at different times. For example, it was calculated that the diameter of the giant Betelgeuse subtends at the earth an angle of 0″·05. A stellar disc of this minuteness is beyond the power of visual detection in even the most powerful telescope, but nevertheless the feat of measuring the diameter of such an insignificant disc was successfully accomplished by means of a great interferometer designed by Professor Michelson and put into commission on Mt. Wilson. We do not propose to describe this instrument nor the optical principles governing its use; it is sufficient to state that in December 1920 the almost incredible achievement of measuring the angular diameter of a star—Betelgeuse—was accomplished. The result turned out to be in almost perfect agreement with the calculated value. This feat stands out as the most notable achievement in practical astronomy of the present century. The parallax of Betelgeuse is known with fair accuracy; it is then easy to calculate the diameter of Betelgeuse in miles. The answer is 250 million miles or three hundred times the diameter of the sun. The average distance of Mars from the sun is about 140 million miles; the diameter of Betelgeuse is not quite the diameter of the orbit of Mars. Betelgeuse is a veritable giant indeed, in bulk as well as in luminosity. The angular diameters of several other stars have been successfully measured in the same way; parallaxes are known, so that the actual diameters can be calculated. These are represented in Figure 97, in which the orbits of the earth and of Mars are shown on the same scale, for purposes of comparison. Let us

summarise: theory predicted that the giant M stars are giants as regards the vastness of their volumes as well as regards their immense luminosities; the interferometer observations leave us no shadow of doubt in this connection and carry a powerful reinforcement to Russell's theory of stellar evolution.

What about the other stars? There is a certain amount of information, as we have seen, regarding the dimensions of certain stars forming eclipsing binaries. Most of these stars are of spectral type B and the diameters vary from about three to eight times the diameter of the sun. One binary of type M is known. The diameters of the component stars of this system are but a little more than half the solar diameter; in volume as well as in luminosity they are but insignificant dwarfs; their density is about four times that of water.

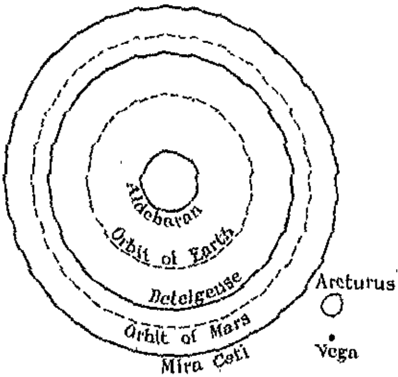



Fig. 97.

Figure 98 illustrates the relative linear dimensions of certain smaller stars. The theory of the evolution of stars from the giants of class M to the intensely hot B type stars, thence down the main series to the dwarf M stars, is apparently complete and unassailable. We shall see later that the use of the word "apparently" is more than a sign of caution.

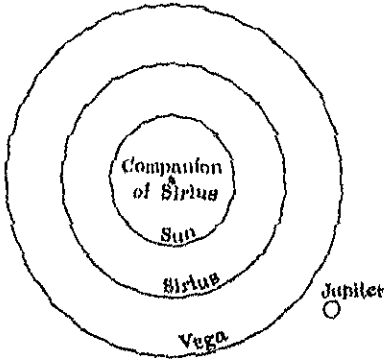



Fig. 98.

An important class of stars which lie outside the evolutionary scheme described in the previous pages is that of the *White Dwarfs*; several are known, of which the companion of Sirius is the most famous. It is believed that the white dwarfs are

comparatively numerous. Let us consider the double star system of Sirius, about which information is remarkably complete. The orbit is accurately known and the masses of Sirius and the companion are known; the masses are about $2\frac{1}{2}$ and 5/6 times the mass of the sun respectively. The companion is 10 magnitudes fainter than Sirius; the latter is thus 10,000 times brighter than the companion. The parallax of the system is known accurately—Sirius, in fact, is one of our nearest stellar neighbours—consequently, the absolute magnitude of the companion can be calculated; it is 11·3. The companion is thus a very feeble dwarf star. Such an absolute magnitude is characteristic of the red dwarf M stars, but the amazing thing is that the spectrum of the companion is of class Fo, stars of which class are of a high surface luminosity. The white dwarfs are consequently well outside the main sequence from Y to Z in Figure 94—their representative dots are somewhere in that part of the diagram near the letter W. Feeble luminosity and intense surface brightness can only mean one thing: the companion of Sirius must be of uncommonly small dimensions. When the diameter of the star is worked out by the method sketched on a previous page, the answer is found to be 24,000 miles. The diameter of the earth is roughly 8,000 miles and that of Uranus, the next planet in order of size, is 32,000 miles approximately. The companion of Sirius—it is to be remembered that it is a star, self-luminous like other stars—is thus of planetary dimensions. But the most astounding deduction has still to be made. If the calculation of the star's diameter is correct, we can immediately calculate the volume; then from the known mass, the average density of the stellar material is easily obtained. The density of the companion is found to be 50,000 times that of water. One ton of its material could be stowed away comfortably in a match-box. For purposes of comparison, it may be added that the densest terrestrial substance known is the metal osmium, some $22\frac{1}{2}$ times denser than water.

Until recently, the possibility of matter with this stupendous density seemed incredible; but no possible flaw could be found in the chain of reasoning. Was there any independent way of testing this result? Einstein's theory of relativity was called upon to provide a positive test. In Chapter VII, we referred

briefly to the slight increase in wave-length of any line in the solar spectrum as compared with the wave-length of the same line produced in a terrestrial laboratory—an increase attributed by the theory to the influence of the sun's mass. A similar effect ought to be produced in the spectrum of the stars. But the magnitude of the effect depends both on the stellar mass and the radius of the star. The mass of the companion of Sirius is nearly equal to that of the sun. Suppose for simplicity the two stellar masses the same (the difference in the masses of the sun and the companion are of course taken into account in the accurate calculation). According to the estimate previously made the radius of the sun is some thirty-six times the radius of the companion. The theory of relativity predicts that the increase of wave-length in a particular line of the companion's spectrum ought to be thirty-six times that of the same line in the solar spectrum. As we have seen in Chapter VII, the effect in the solar spectrum is just large enough to be detected; the effect in the companion's spectrum ought then to be easily measured. Now the amount of the displacement of a line in a star's spectrum relatively to the corresponding line in the comparison spectrum is taken as the foundation of the measurement of radial motion (for the ordinary star, the relativity displacement is negligible). It is convenient, then, to describe the relativity displacement in terms of radial velocity, that is, as so many kilometres per second. The exact calculation —still based on the previously estimated value of the companion's radius—is that the companion's spectrum should show a fictitious velocity of recession of 20 kilometres per second. If the white dwarf was a single star, that is, not a component of a binary system, for example, this spurious velocity could not be disentangled from a genuine radial velocity. As it happens, the separation in the present instance is comparatively simple. The lines of the companion's spectrum when measured indicate a certain radial velocity. This includes: (1) the fictitious radial velocity of the relativity effect; (2) the radial velocity of the binary system as a whole; and (3) the orbital velocity (or rather, that part of it in the line of sight) of the companion around the centre of gravity of the system. The last two can be calculated from the observed radial velocity of Sirius itself and the particulars of the binary system. Consequently the

relativity effect can be deduced. Dr Adams carried out the test at Mt. Wilson Observatory in 1925 and found the Einstein effect to be 19 kilometres per second—almost in exact agreement with prediction. As Professor Eddington puts it: "Dr Adams has killed two birds with one stone; he has carried out a new test of Einstein's general theory of relativity and he has confirmed our suspicion that matter 2000 times denser than platinum[1] is not only possible, but is actually present in the universe."

The Russell theory of giants and dwarfs is a great historical landmark in the progress of astronomy. We have seen how the theory has been reared on a vast mass of observational evidence and fortified by the spectroscopic work of Dr Adams and the interferometer measures of the angular diameters of the stars. We turn now to the remarkable mathematical researches of Professor A. S. Eddington on the internal constitution of the stars. It is not possible within the compass of a few pages to do more here than give a brief outline of these; the reader will find an enthralling story in Professor Eddington's book on "Stars and Atoms." Consider a giant star like Betelgeuse, composed of gas in an extremely tenuous state, in the condition known to the physicist as that of a perfect gas to which known physical laws apply. The vast globe is pouring out radiant energy in the form of heat and light which must originate within the star. As we go inwards into the star, the temperature of the gas increases and the pressure of the gas increases. At any point in the interior of the star, there is a balance of forces. From above there is the weight of the superincumbent gas pressing downwards; pressing outwards is the elasticity of the gas, like the air in a pneumatic tyre. The elastic properties of a gas are explained by the activity and number of the particles of which it is composed. The greater the number of particles of air pumped into a motor tyre, the greater is the elasticity (or pressure) and consequently the greater the support given to the car. Also, the higher the temperature of the air, the greater is the elasticity. A motor tyre, pumped hard at ordinary temperatures, would go "flat" if placed in a refrigerator, and would probably burst if placed in a room kept at a temperature of several hundred degrees. At a point

[1] The density of platinum is $21\frac{1}{2}$ times that of water.

within the star there must be some definite connection between the density and temperature of the gas such that the weight of the layers above may be supported. Proceeding step by step towards the centre, the temperature and density at successive points are calculated; finally the central temperature is found. But the law according to which the density alters from the outside of the star inwards enables the total mass of the stellar material to be calculated. The mathematical model is thus brought into direct comparison with the stars in the sky. But one important influence within the star has been omitted in the above considerations. In Chapter VI, in describing the problem of the solar chromosphere, we referred to an important agency, the pressure of radiation. Professor Eddington has calculated that the central temperature of the sun is not far from 40 million degrees centigrade; thus within the star, the influence of radiation pressure becomes of paramount importance. We have to revise our picture of the balancing forces at a point within the star; to the natural elasticity of the gas, we must add the outward pressure due to radiation which depends, as regards magnitude, on the manner in which the temperature alters from point to point in the interior.

Two questions naturally suggest themselves at this juncture. Does the nature of what we have called "gas" not make some difference in the calculations, for surely the chemical constitution of a particular star is hardly likely to be matched exactly or even approximately in any other? And the other question is: "What is the nature of this radiation that appears to play such an important part in the delicate balance of internal stellar conditions?" Let us consider the first question. If pure oxygen is pumped into a tyre, the elasticity of the oxygen—or the pressure of the gas—depends on the energy of motion of the particles (and of course on their number). The particles in this instance are molecules. The energy of motion of the molecules depends on their mass—usually referred to in terms of "molecular weight"—and on their velocity. All this is straightforward when we are dealing with a single gas such as oxygen; but how can progress be made in an intricate calculation when the stellar material probably consists of several or all of the familiar terrestrial elements in unknown proportions? Within the star, the atoms of the elements, whatever they may be, are

unable to remain intact; the physical conditions are too severe, and they are stripped of most of their planetary electrons. The particles which are responsible for the gas pressure at any level within the star are a motley crew of atomic nuclei, atoms with a mere fringe of planetary electrons, and electrons. At first sight, the problem is beset with further intolerable complications. Actually, the situation is very different. In calculating the gas-pressure what matters is the average molecular weight of the particles, and as electrons (of negligible mass) count as discrete particles, the average molecular weight can be estimated with considerable accuracy if the ionisation of the atoms, whatever their chemical origin, is complete or nearly so. The atom of iron, for example, is of atomic weight 56 as compared with that of the hydrogen atom taken as the unit; the iron atom consists of the nucleus and twenty-six planetary electrons, the latter's contribution to the atomic weight being negligible. If the iron atom is completely ionised, there are now twenty-seven discrete and independent particles and the average molecular weight is therefore fifty-six divided by twenty-seven or about 2·1. A similar calculation for any other element—other than hydrogen—would give a result not differing greatly from two. In this way, Professor Eddington was enabled to disregard the chemical constitution of the stars and to make his calculations apply to any star in the sky.

To answer the second question, let us first consider a blue star and a red star. Blue light is of shorter wave-length than red light, and the difference in colour of the two stars is due to the difference in the surface temperatures of these stars. High temperature is associated with the shorter wave-lengths, low temperature with the longer. Within the star the temperature may be as high as 40 million degrees, and the radiation is of very short wave-length of the type known as X-rays. Again, when we were discussing the photographic observations of Mars, we referred to the greater ability of the red constituents of the sun's light to penetrate the planet's atmosphere as compared with the blue constituents; the Martian atmosphere was, so to speak, opaque to the light of the shorter wave-lengths. Something of the same kind occurs in the stars; stellar material is, in fact, exceedingly opaque to the short wave-length radiation, and the coefficient of opacity regulates the rate at

ıtion escapes from one level in a star's interior ɔl. The opacity of the stellar material evidently rtant part in the theory. Actually, the deter- ɜ coefficient of opacity is one of great difficulty ɹusible hypotheses have been made which allow ɿathematical argument concerning the internal the stars to march towards a theoretical con- can then be confronted with the observed of the stars.

rief, are the main considerations governing the ı Professor Eddington set himself to solve. Let ne of his results.

ɜeen that at thin a star ɔf the outer is afforded pressure (the the gas) and pressure. It ; the ratio of pproximately roughout any ıt us assume ty that the tly the same. total outward

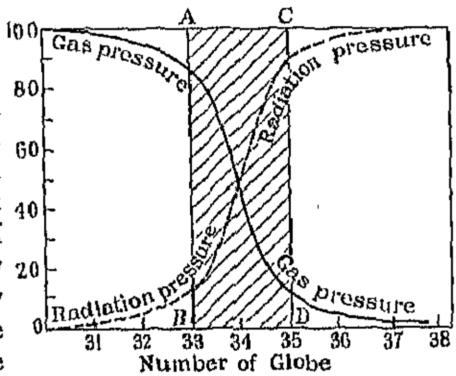



FIG. 99.

percentage arising from the gas pressure and ıdiation pressure can be calculated. Professor akes a series of models as follows. The first of gas of mass 10 grams, the second of 100 third of 1000 grams (this globe is about 2¼ d so on; the mass (in grams) of the 30th ɜxample, would be written as 1 followed by 30 'o each globe, supposed isolated in space, the apply; in particular, the percentage of gas pressure iation pressure) in relation to the total outward be found at any point within the particular globe. ɿre illustrated in Figure 99. For example, consider er 31. The figure shows that the calculated gas ractically 100 per cent. of the total outward pressure

and that the radiation pressure is negligible. What does this imply? It means that such a globe is unable to radiate at all; in other words, that it can never attain by its own efforts to the glory of a self-luminous star. The mass of the 31st globe is just five times that of the planet Jupiter, the most massive planet. If there are bodies of planetary mass roaming the universe, their existence will only be revealed (if at all) by indirect methods. Consider now globe number 33. About 89 per cent. of the total outward pressure is gas pressure and the remainder, 11 per cent., is radiation pressure. At this point radiation pressure has to be seriously taken into the reckoning; the globe will radiate—faintly no doubt—as a feeble self-luminous star. In the shaded area—between the lines AB and CD—the radiation pressure increases in importance until for the 35th globe it is no less than 85 per cent. of the total outward pressure, the remainder, 15 per cent., being the gas pressure. Beyond the 35th globe the gas pressure fades away into relative insignificance and the total outward pressure is almost entirely radiation pressure. As Professor Eddington puts it: "Regarded as a tussle between gas pressure and radiation pressure, the contest is overwhelmingly one-sided except between Nos. 33 and 35, where we may expect something interesting to happen. What 'happens' is the stars."

The mass of globe No. 33 is just half the sun's mass and that of globe No. 35 is fifty times the sun's mass. The least massive star known is a little less than half the mass of globe No. 33; the most massive star known just exceeds in mass globe No. 35. Below No. 33, a globe is unable to shine; somewhat beyond No. 35, radiation pressure is of such paramount importance as to jeopardise the stability of the star. Surely this is an extraordinary achievement; by abstract reasoning based on the known physical laws, the mathematician is able to *predict* the stars.

Until the beginning of 1924 the Russell theory of stellar evolution maintained its position as an article of astronomical belief, for it fitted in so well with a wealth of information concerning the absolute magnitudes, densities, spectral types and dimensions of the stars. There is, however, one other important property of the stars, namely, mass. In 1913, when the knowledge of stellar masses was scanty, it was noticed never-

theless that the hotter stars were more massive and the dwarf stars were less massive than the sun. This was taken to mean that it was only the most massive stars that could run the complete course of the Russell diagram (that is, in Figure 94, from X to Y and then down the main series from Y to Z) and that stars of small mass might only get as far as type F, for example, before passing through the successive stages (from type F to M) in a dwarf star's career. Professor Eddington's researches in 1924 put a new aspect on the evolutionary theory. Let us see what these were. In the first instance, they consisted in the comparison of theory and observation for stars of known

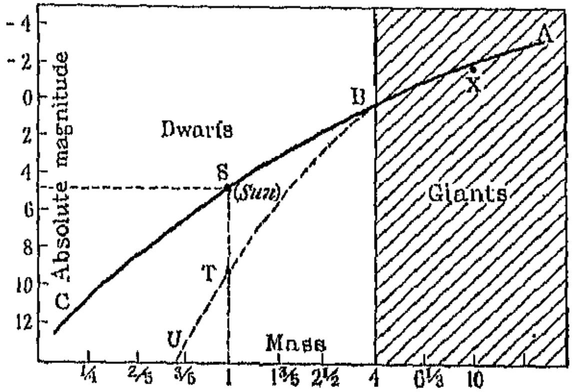



FIG. 100.

mass and luminosity (or absolute magnitude), and in the second the relationship of the new ideas to the theory of stellar evolution. The theory of which we have been speaking concerns giant stars, that is, stars whose material is in the condition of a perfect gas. A perfect gas is characterised by the freedom of movement of its molecules (or particles); if the latter are squeezed together as in a gas under severe pressure, the simple gas laws break down. A giant star is thus an assemblage of gas "particles" in a condition suitable for the mathematical application of the known physical laws. The theory established a relation between the mass and the luminosity (or absolute magnitude) of stars in the condition of a perfect gas; if the mass of such a star was known, its absolute magnitude could

be predicted. This is illustrated in Figure 100. The curve ABC is the theoretical curve—every point on it corresponds to a diffuse star of a particular mass and of a particular absolute magnitude. Thus the point B indicates that a diffuse star of mass four times the solar mass will be of absolute magnitude 0—corresponding approximately to Capella. The part of the curve to the right of B—in the shaded area—refers evidently to the class of stars described as giants. Professor Eddington utilised all the trustworthy information concerning the masses and luminosities of a fair number of stars. Each star contributed a dot to the diagram. For example, if a certain star was known to be of mass ten times the solar mass and of absolute magnitude −2, the representative dot would be somewhere vertically above "10" on the horizontal scale and also on the horizontal line drawn through absolute magnitude −2 on the vertical scale; the representative dot in this instance is thus at X. For the giant stars, the representative dots lay on or near the theoretical curve between A and B (such small discrepancies as there were may be safely attributed to the inevitable errors of observation). So far observation confirmed theory. What about the dwarf stars? These are dense stars in which the gaseous matter is tightly compressed beyond the point where the gas laws were believed to fail. Presumably, the greatly different pressure-conditions in the dwarf stars would lead to another curve coalescing with the theoretical curve ABC (which, it must be emphasised again, related to stars in the condition of perfect gas) somewhere near B in the diagram where the gas laws were believed to break down. Professor Eddington expected that the representative dots of the dwarf stars would lie on some such curve as BTU (shown dotted). But the dwarfs falsified this expectation completely. The dots all lay on or near the curve BC. The dense stars, in fact, conformed entirely to the theory of stars in the condition of a perfect gas. The only conclusion must be that the dense stars *are* in the condition of a perfect gas. What is the explanation of such an apparently absurd statement, for is not the gaseous material of the sun, for example, $1\frac{1}{2}$ times denser than water? The answer is to be found in the high degree of ionisation of the atoms within the star. In a terrestrial gas, such as our atmosphere, the atoms have their full array of electrons, circulating in orbits around

the nuclei; the size of an atom is therefore dependent on the dimensions of the outer electronic orbits. There is a limit to the number of atoms, which can be packed into any given volume, if a particular degree of mobility is to be accorded to the atoms. Squeeze more in; you increase the density of the gas and decrease the freedom of the atoms. A stage is reached eventually when the atoms are packed so tightly that nearly all mobility is denied them—as when a gas is liquefied or solidified. At some point in the concentration of the atoms, the gas-laws break down. Consider now the atoms in a star. Some are stripped of all their electrons; others have but a few of the inner electrons remaining. The "size" of the stellar atoms is diminished enormously. Very many more can then be packed into a given volume to give the same or a similar degree of mobility as for the more voluminous atoms of a terrestrial perfect gas; in other words, the gas density can be very greatly increased without the stellar material departing from the condition of a perfect gas. Professor Eddington has estimated that any star with an average density not exceeding 1000 times that of water ought to behave as a perfect gas. Thus, with the exception of the white dwarfs, the stars whether great or small are brought within one and the same category and are subordinate to the same physical laws.

But the accordance between observation and theory, illustrated in Figure 100, has a wider significance. The masses of only a relatively small number of stars are known with any certainty, whereas the parallaxes and luminosities of several thousands have been measured. The curve in Figure 100 enables the mass of any star whose absolute magnitude is known to be estimated at once. In this way, several researches in which a knowledge of stellar masses is required have led to interesting results; we do no more than mention this new line of attack.

Let us now see how the results of Professor Eddington's theory joins issue with the Russell theory of stellar evolution. At the outset, it should be stated that there is no dispute about the characteristics of the stars whether giants or dwarfs as illustrated in the Russell diagram (Figure 94). But the particular part of the latter theory which explained the turning point (at Y) in the progress of giant stars along XY and down

the main series YZ, in terms of the failure of the gas laws, now seen to be untenable—for the dwarfs like the giants a in the condition of a perfect gas. Let us further consider greater detail the characteristics of the stars of the spect types, A, G, M, on the main series YZ (Figure 101). Star is more luminous than G and G than M; the mass-luminosi law (Figure 100) determines the masses of the stars (the sun mass being taken as 1). The densities shown in Figure 101 a in terms of the density of water taken as 1. The sequen AGM is a sequence of diminishing mass, of increasing densit and of diminishing surface temperature and therefore diminishing surface brightness. Also one of the significan

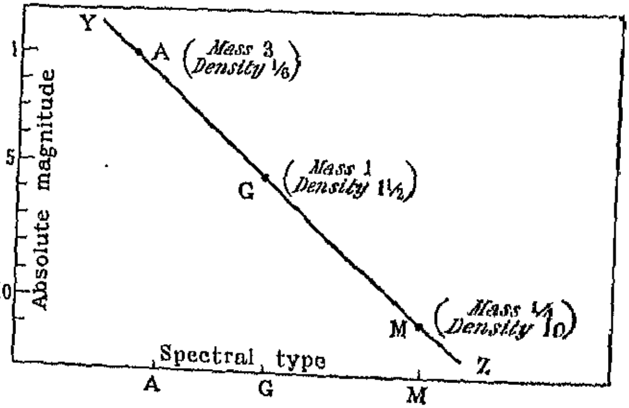



FIG. 101.

facts which emerges from Professor Eddington's theory is tha in these very diverse stars, the central temperature is practically identical, namely, about 40 million degrees centigrade. I stellar evolution has any meaning at all, then it seems clea from the Russell diagram that there are only two ways by which the stars of the main series can evolve—either the progress of evolution is in the direction from A to G to M or in the reverse direction. There is little to be said in favour of the latter alternative; let us look at what the former implies. If a star is at some time in its history at A and at some subsequent time evolves into a star such as G, the evolution must be accompanied by a loss of mass—star A must, in fact, get rid of two-thirds of its mass before it can function as a star G.

Similarly the sun (star G) must lose about three-quarters of its mass before it reaches the red dwarf stage (star M). But how can a star lose its mass? The pressure of radiation may, and probably does, drive off into space a steady stream of atoms from the sun's chromosphere. But this suggestion is totally inadequate to explain but an inconspicuous decrease of stellar masses. We know, however, that the sun and every star are pouring forth vast quantities of heat and light energy. According to the theory of relativity, energy and mass are inter-related terms; a loss of energy can therefore be described as a loss of mass, and if the former is known the latter can be calculated. In this way, it is found that, by the apparently simple process of radiating light and heat, the sun is losing mass at the rate of 4 million tons per second! Clearly this loss of energy—or mass—cannot go on for ever. The sun's capacity to shine cannot be imagined on any grounds to be inexhaustible. Whence come the vast stores of energy in the sun, so prodigally radiated into space? Half a century ago, Helmholtz and Lord Kelvin put forward what is still known as the contraction theory. The sun (or any star) is gradually contracting and the constituent particles are falling under the influence of gravitation ever nearer the centre of the globe. There is a gradual conversion of potential energy into heat energy which goes on as long as contraction is possible; in this way the sun (or any star) acquires the necessary supply of energy which maintains its capacity to shine. The theory is mathematically correct, so far as it goes, but does it fit the facts? It is a comparatively simple matter to calculate the time required for the sun to contract from a great diffuse globe of gas to its present dimensions. In round figures, it is 20 millions of years. At some stage in the sun's history, the earth and the planets were formed from the sun and therefore the age of the earth cannot be more than 20 million years. But this is where the contraction theory comes into conflict with a mass of geological (and other) evidence. The element uranium disintegrates at a known rate, which has been definitely measured, into (amongst other things) lead. The percentage of lead in any uranium mineral allows a reliable estimate to be made of the age of the mineral and thus gives some clue to the age of the earth—or rather of the earth's solid crust. The answer is 1300 million years. There is other

evidence in corroboration of this estimate. The sun's age must be greater still—it cannot be much less than 2000 million years. The conclusion is definite; the sun must draw its supply of energy from more sources than that contemplated in the contraction theory. There is only one possible additional source—the energy within the atoms themselves, that is, subatomic energy. How this energy is liberated no one can say, and until this mystery is solved, the problem of stellar evolution is completely at a standstill. Sir J. H. Jeans has suggested the annihilation of matter in the deep interior of the star, caused by the falling together of a positively charged proton with a negatively charged electron; these, so to speak, cancel out and what is left is a packet of energy in the form of radiation. The star, in order to live, must destroy itself, at least partially; in plainer terms, the star radiates away its mass. Moreover, the supply of energy so liberated is more than sufficient for the most exacting demands of geological science.

Let us now return to the problem of stellar evolution. A star of spectral type A and mass three times that of the sun can only evolve into a star similar in all respects to the sun by losing two-thirds of its mass (see Figure 101). If radiation of mass by the annihilation of matter within the star is more than a mere speculation, such evolution is then possible and the Russell course of evolution retains its principal features. It is even possible to calculate the duration of various stages in stellar evolution. If our sun were at one time as massive as star A (Figure 101), that is, three times its present mass, a period of about 6 to 7 million million years is necessary. If the sun started its career as a very massive star, its age must be somewhat longer—in round figures, we may take it to be 7 million million years, defined conveniently as the cosmogonic unit of time. If the sun will ever evolve into a red dwarf of mass one-quarter of its present mass, no less than 80 cosmogonic units of time will be necessary for the process. Such figures stagger the imagination. The hypothesis of the radiation of mass gives the sun an antiquity far exceeding that regarded as a minimum by geologists; it predicts, too, a still longer future career as a luminous star.

The radiation of mass is a hypothesis shrouded in mystery; one of its many implications is more mysterious still. It was

stated on page 256 that the central temperatures of the three typical stars A, G and M (Figure 101) are identical, namely, 40 million degrees centigrade approximately. The different rates at which energy must be released in the three stars can be calculated—that is, the rate at which stellar matter must be annihilated; the rate so found is greatest for A and least for M. Professor Eddington describes the situation as follows: "It seems extraordinary that stars requiring such different supplies should have to ascend to the same temperature to procure them. We can scarcely believe that there is a kind of boiling-point (independent of pressure) at which matter boils off into energy. The whole phenomenon is most perplexing."

We began this chapter by describing an evolutionary theory that at one time apparently satisfied astronomical observations very beautifully. In 1924 the whole scheme was thrown into serious doubt by the discovery of the relation between stellar mass and luminosity. What is the position to-day? The conception of stellar evolution on Russell's lines can only be maintained by an appeal to a process—the annihilation of matter or some similar sub-atomic release of energy—which is, perhaps from the physicist's point of view, more speculative than certain. From the astronomer's point of view the appeal has claims to be entertained seriously. We may remind the reader that the age of the sun must be greater than the simple contraction theory allows, and it seems inevitable that the sun must draw—to a limited extent, at least—on its store of sub-atomic energy, how released we do not know. The annihilation of matter in the sun would provide more than an ample supply. If this copious supply is denied, the sun is capable of comparatively little change and evolution along the main series becomes impossible. We seem to have reached a deadlock and we must await an answer to the questions: "How is sub-atomic energy released? Is it by the annihilation of stellar material or by some kindred process of which we have yet no inkling?" According to the answer, the evolution of the stars in the sense described stands or falls.

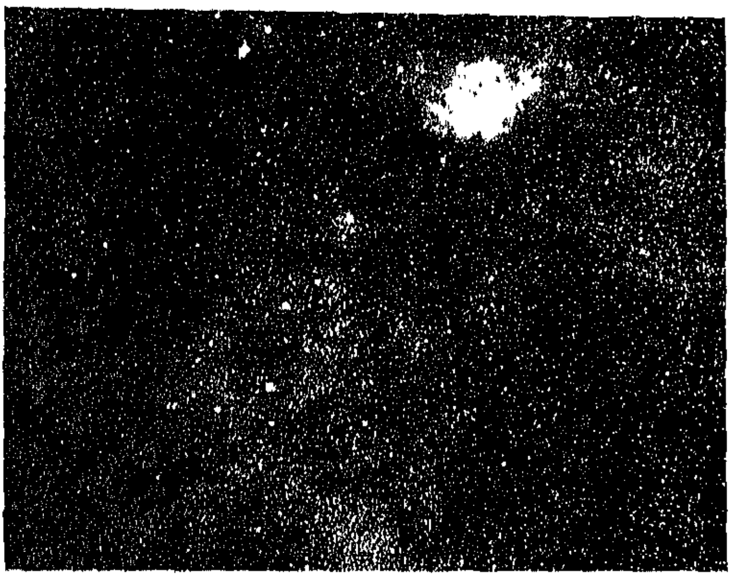
# CHAPTER XVI

## STAR CLUSTERS AND NEBULÆ

Star clusters are divided into two classes—the *open* clusters and the *globular* clusters. Of the former, about 200 are known. With one exception, the open clusters are found in or near the Milky Way. The Pleiades is one of the best known clusters of this type; as it covers a not inconsiderable region of the sky, membership of the system has to be decided according to some common property such as proper motion. This is the criterion which was applied in Chapter XIII (Figure 81) to the members of the Taurus Cluster, which covers a much larger area of the sky than the Pleiades. For many clusters, the proper motion of the individual stars is so small that it is difficult to decide which stars really belong to the cluster and which to the general stellar background.

Without a doubt, the open clusters are aggregations of stars all moving in parallel directions with the same speed through the great stellar system. One of the most interesting clusters is that known as the Ursa Major Cluster, consisting of about 20 members scattered over an extensive area of the sky: it includes five of the seven bright stars of the 'Plough' and also Sirius. The proper motions and the radial velocities of most of the stars in this cluster have been measured, and by the method illustrated in the case of the Taurus Cluster (Figure 82) the distances of the individual stars are obtained. It is found that this cluster is a flattened system—the members of it lie almost in a plane—and that the direction in which the cluster is moving is almost at right angles to this plane.

We consider now the globular clusters—for an example, we refer the reader to Plate I, where a photograph of the great star cluster in the constellation of Hercules is reproduced. The number of these wonderful objects is but 69. They were first catalogued (in 1781), together with certain of the more



Two Regions of Milky Way photographed by Barnard, showing Dark Nebulae.
*Yerkes Observatory of the University of Chicago.*

conspicuous nebulæ, by the astronomer Messier, and they are still generally known by the catalogue number; the cluster in Hercules is No. 13 in Messier's list and is usually known as M. 13. The *New General Catalogue* of Dr Dreyer (1888), together with the more recent appendices, contains about 13,000 entries of open and globular clusters and of nebulæ; the catalogue number, prefixed by the letters N.G.C., indicates the particular object concerned.

The number of stars in an open cluster rarely exceeds a few hundreds; in the globular clusters, the stars are counted in thousands. The open clusters lie within and are part of the stellar system; the globular clusters are independent collections of stars on the fringe of, or well outside, the stellar system. From even a casual inspection of the photograph of M. 13 (Plate I), the difficulty of counting the stars in the cluster is immediately apparent, and the difficulty is not in any way minimised when still longer exposures are made which reveal still fainter stars. In a system such as M. 13 the number of stars is hardly likely to be less than 100,000.

One of the great achievements of recent years has been the measurement of the distances of globular clusters. For a long time it had been realised, from the apparent faintness of even the brightest stars in the cluster, that the ordinary trigonometrical method of measuring stellar distances would be of little avail when applied to the clusters. In a previous chapter we discussed the class of variable stars known as Cepheids and also the relation between the absolute magnitudes of these stars and the periods of light variation. In the globular clusters, there are many variable stars with the characteristics of the Cepheids. From a series of photographs, the light-curve of any cluster variable can be obtained and, in particular, the period of its light variation can be found. Then by reference to the luminosity-period curve (Figure 93), the absolute magnitude of the variable is deduced. The apparent magnitude is measured in the usual way. Both the absolute magnitude and the apparent magnitude now being known, the distance of the variable is easily calculated; this is, in effect, the distance of the cluster. Such, in brief, was the principal line of attack initiated by Dr Shapley at Mt. Wilson. His results gave the first conclusive evidence as to the vast dimensions of the visible

universe. It will be sufficient to indicate the distances of the nearest and most remote clusters; the nearest is the great cluster in Centaurus in the southern sky, about 20,000 light-years away; the most distant is 230,000 light-years away. The imagination is staggered in its effort to grasp the stupendous extent of the universe revealed by Dr Shapley's researches. But there is another aspect of infinite importance. Observation shows that the globular clusters are constituted very much alike; they contain the same types of stars, giant red stars of spectral class M and so on. One cluster we see to-day as it really was 20,000 years ago when the light, which now impresses our photographic plates with its message, commenced its long journey through inter-stellar space; another cluster we see as it was 230,000 years ago. If stellar evolution were at all a rapid process, surely 200,000 years would leave a mark on the characteristics of the cluster stars. There is not the least suspicion of any difference between the general nature of the stars in the nearest and in the most remote cluster; stellar evolution, it is inferred, must be such that a million years are as a moment in human history.

The distance of a globular cluster being known, it is then possible to calculate the diameter of such a stellar system, for the angular diameter can be inferred from the photographs. For M. 13, the diameter is found to be at least 100 light-years. Compared with our own system of stars, the dimensions of a globular cluster are evidently small; for our telescopes can measure directly star distances approaching 1000 light-years and that is by no means the limit to the extent of the stellar system. The star nearest the sun is about 4¼ light-years distant, and if this is taken as an average distance between any two neighbouring stars the number of stars in any given volume of the stellar system can be easily calculated. It is only necessary to make a rough calculation to show that the stars in a globular cluster must be at least a hundred times more closely packed together than the stars in our stellar system. But even so, the cluster stars are distributed on a most generous scale; they are so far apart that light will require several months to cross the void separating one star from its closest neighbour.

The spectroscope shows that the globular clusters are moving

PLATE XV

The Great Nebula in Orion.

*Mt. Wilson Observatory.*

with high velocities in the line of sight; the average velocity is about 75 miles per second. If the cross-velocity is of this order of magnitude, it is evident that the proper motion of the clusters must be exceedingly minute and probably beyond the capacity of measurement of even the most powerful telescopes. Indeed, this is precisely what Dr van Maanen found as regards the great cluster M. 13, but as the interval between the proper motion plates was no more than 10 years, a positive result was hardly to be expected. However, it may be possible after an interval of 50 years or so to measure the very minute proper motions of the nearest globular clusters.

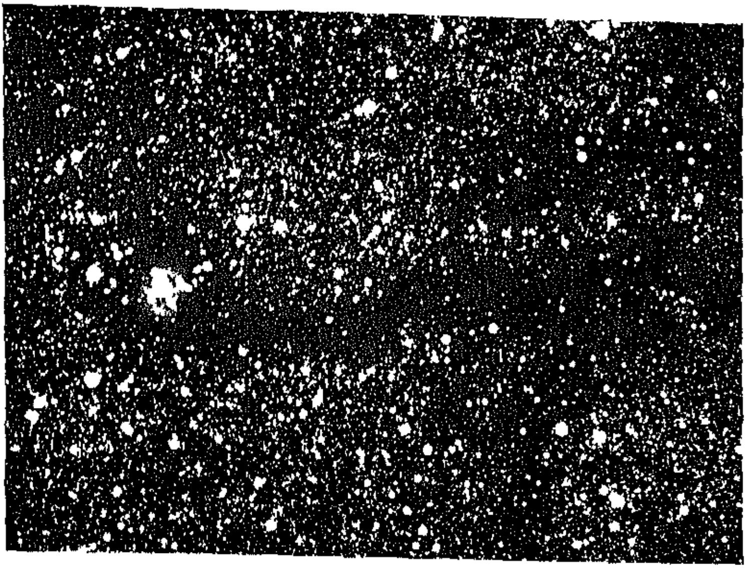
The nebulæ are divided into several classes, according to their characteristics, as follows: dark nebulæ, diffuse luminous nebulæ, planetary nebulæ and spiral nebulæ. The first three classes are found only in or near the region of the Milky Way, the last class remote from the Milky Way.

To Sir William Herschel the dark nebulæ, as we know them now, represented great voids in the heavens as if some supernatural agency had swept great regions of space free of stars. For instance, he noticed that in the constellation of the Scorpion there was a vast dark area in which not a single star was visible, while all around it the stars were scattered in rich profusion. To Herschel it seemed that some parts of the stellar universe had suffered much more severely than others. Now it is believed that the dark regions of the Milky Way are the evidence of great obscuring clouds—dark nebulæ—which hide the light of the stars beyond. The photographs in Plates XV and XVII (*a*) will give the reader a good idea of the effect of these vast obscuring clouds in the heavens.

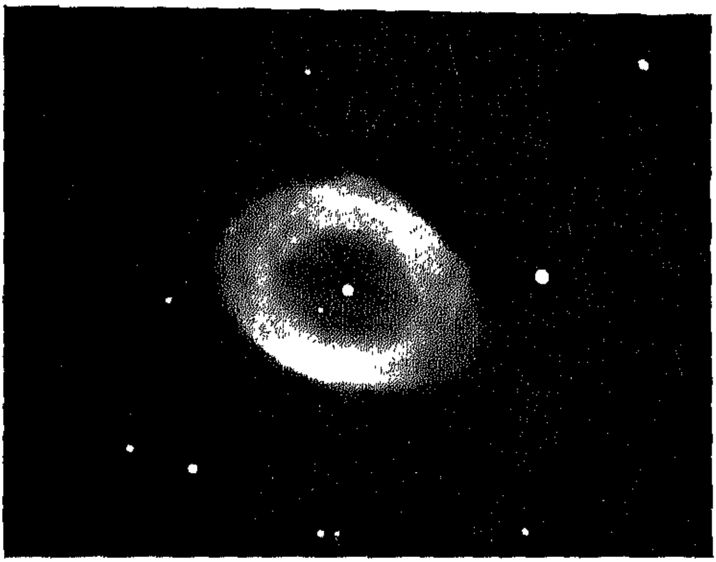
Of all astronomical photographs, perhaps the most beautiful are those of the great diffuse luminous nebulæ, two of which are reproduced in Plate XVI (the great nebula in Orion) and in Plate I (the Trifid nebula, M. 20). The spectroscope can evidently furnish important information respecting these beautiful objects. The spectra of some diffuse nebulæ consist only of a number of bright lines, evidently due to a luminous gas or gases in a very rarefied state, while the spectra of others show dark absorption lines on the bright background of a continuous spectrum. Several of the bright lines—notably two in the green part of the spectrum which

account for the peculiarly greenish tint of the nebulæ in the telescope—remained unidentified, until recently, with known terrestrial elements. These are the so-called *nebulium lines*, originally believed to be due to an unknown element nebulium, to which reference will later be made. A great advance in the interpretation of the diffuse nebulæ was made in 1924 by Dr E. P. Hubble at Mt. Wilson. He showed conclusively that the luminosity of the nebulæ must be attributed to the influence of neighbouring bright stars. For example, in the great Orion nebula there is a bright multiple star, and long exposure photographs of the Pleiades show extensive wisp-like nebulosity surrounding the brightest stars. But that is not all. The diffuse nebulæ with bright line spectra were found to be associated always with the hottest stars of type O and B0, while the nebulæ with the absorption line spectra were found to be associated with cooler stars of the classes B1 to B9, A, F, G and K. On this view the luminosity of the nebulæ is attributed mainly to the influence of the associated star or stars; without the latter the nebula itself would probably have the same characteristics as the dark nebulæ to which reference has just been made. As regards the diffuse nebulæ with absorption spectra, it is quite possible and even probable that these nebulæ appear bright as a result of the reflection from their constituent particles, whether of finely divided dust or of rarefied gas, of the light from the stars connected with them. But this explanation cannot hold for the bright line nebulæ. The very intense radiation emitted by the hot stars must be able to stimulate certain of the gaseous elements of the nebula to luminosity, and prominent among these elements is nebulium. The distances of one or two diffuse nebulæ have been estimated by indirect methods. From a study of the proper motions of stars apparently connected with the great nebula in Orion, Kapteyn assigned the distance of 600 light-years to this object.

Over a hundred planetary nebulæ are known. One of the most beautiful planetary nebulæ is the Ring Nebula in the constellation Lyra, shown in Plate XVII (*b*). Of 78 objects of this class visible in the northern sky, there are 56 with central stars. The central stars are invariably of spectral type O—the hottest stars—and then the spectrum of the



(*a*) The Cocoon Nebula and Dark Nebulae.
*Prof. M. Wolf.*



(*b*) The Ring Nebula in *Lyra*.
*Dominion Observatory, Victoria, B.C.*

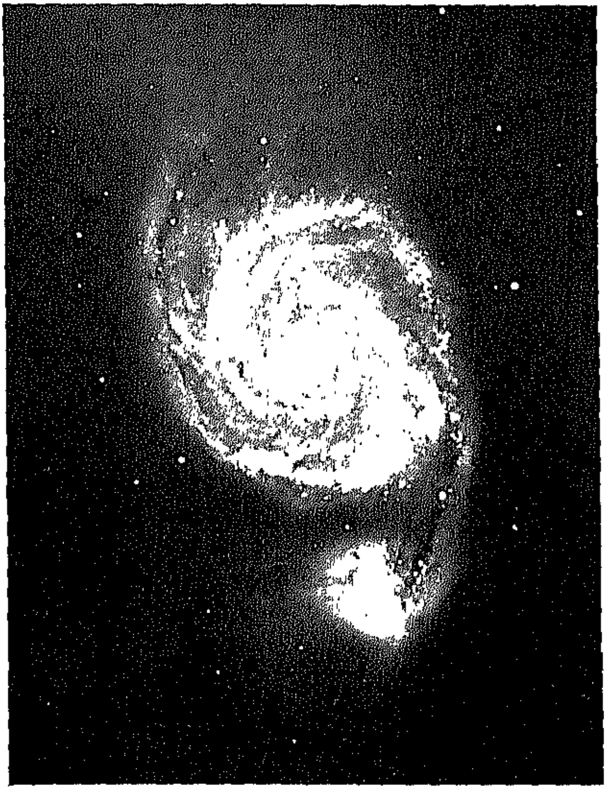
nebula is a bright-line spectrum with the green nebulium lines prominent as in the diffuse nebulæ. Other nebulæ of this class produce a dark-line spectrum. We have seen that new stars (Novæ) several months after their outburst settle down into stars of type O, and are sometimes surrounded by a nebulous envelope. These facts have suggested that the planetary nebulæ, as a class, represent a stage in the life-history of a nova long after the outburst which raised it to the highest pinnacle of splendour. The radial velocities of a number of planetary nebulæ have been measured; the average is about 25 miles per second; their space velocities must therefore be very much greater than the average space velocity of the stars. The measures of parallax made at Mt. Wilson indicate that the diameters of the gaseous shells must be at least several hundred times greater than the diameter of the solar system.

Towards the end of 1927 the mystery surrounding the origin of the unknown lines in the bright-line spectra of the diffuse and planetary nebulæ was cleared up. It had been realised for a long time that the lines in question did not arise from an element or elements still undiscovered, but that they must be due to one or more familiar elements existing under unfamiliar conditions. Here was a problem in which the astrophysicist and the theoretical physicist could usefully collaborate—the former in providing accurate measures of the wave-lengths and intensities of the unknown lines, the latter in applying the principles of atomic theory to the states of the ionised atoms of the elements. Dr I. S. Bowen of Pasadena is the solver of the mystery—nebulium is none other than the chief constituents of the air we breathe, namely, oxygen and nitrogen, the atoms of which, in the extremely rarefied nebular gas, are in a singly and doubly ionised condition.

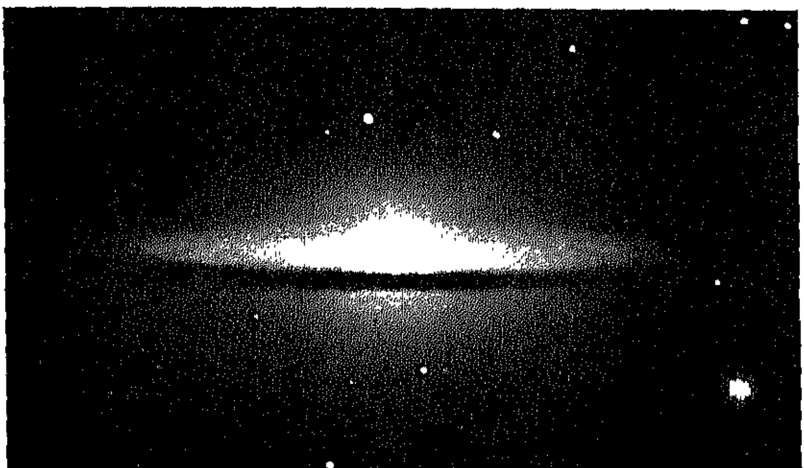
We come now to the spiral nebulæ, which are found in the regions of the sky outside the Milky Way; with the spirals, we ought to mention the lens-shaped nebulæ (which may be spiral nebulæ seen edge-on), the elliptical and globular nebulæ of regular shape. Plate XVIII (*a*) shows an example of the spiral nebula family, and on Plate XVIII (*b*) is shown a photograph of a lens-shaped nebula, N.G.C. 4594, with a dark obscuring band of nebulosity. The spiral character of

these objects was first discovered in 1845 with Lord Rosse's great reflector in Ireland. The early spectroscopic observations were conclusive in one respect; these nebulæ could not be immense masses of glowing gas, like the diffuse nebulæ, but, in the main, aggregations of stars. The deduction was made from the nature of the spectra which bore a remarkable resemblance to the dark-line spectra of the F and G type stars. Recently part of the cloud-like structure of the great nebula in Andromeda (Plate XIX) has been shown, by means of long exposure photographs, to be vast swarms of extremely faint stars. The spectroscope has also been successful in measuring the line-of-sight velocities of several of the brightest spirals. Nearly 90 per cent. of these radial velocities are velocities of recession—the largest so far measured is the stupendous speed of 1100 miles per second away from the sun. The largest spiral, that in Andromeda, has a radial velocity of approach of 200 miles per second.

Until recently, the question as to the distances of the spiral nebulæ was one of lively dispute between two schools of thought. There was, firstly, the belief that the spirals were at moderate distances, and, secondly, the view that they must be at almost inconceivably great distances; the latter view is summarised in the statement that the spirals are *Island Universes*, remote from our own stellar system and comparable in size with it. Is it possible to estimate the distance of a spiral nebula like that in Andromeda? Two lines of attack have been developed—the first from the observations of novæ in the nebula and the second from the observations of Cepheid variables. In 1885 the first nova was discovered in the Andromeda nebula. At the summit of its outburst it reached apparent magnitude 7; with our present-day ideas as to the distance of the nebula, this star at its brightest must have been 100 million times brighter than the sun. Since then over 80 novæ have been discovered and studied in this nebula. Now from such stars as Nova Persei (1901) and Nova Aquilæ (1918), discussed in a previous chapter, it is possible to derive fairly accurate information as to the average absolute magnitude of these stars when they reach their greatest brightness. If the novæ in the spiral are at all comparable with these, the average absolute magnitudes of the former may be inferred and therefore from the observed apparent



(*a*) The Spiral Nebula M. 51 in *Canes Venatici*.
*Mt. Wilson Observatory.*

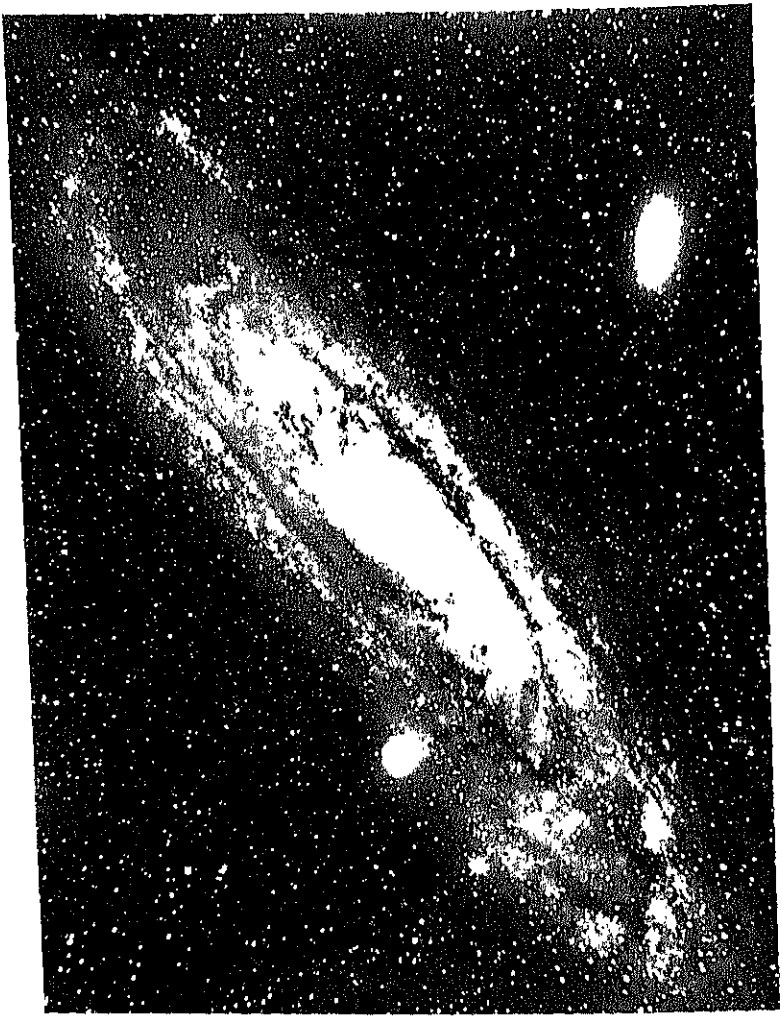


(*b*) Lens-shaped Nebula N.G.C. 4594 in *Virgo*.
*Mt. Wilson Observatory.*

magnitudes the distance of the spiral can be obtained. A much more reliable estimate of the distance of the Andromeda nebula, however, has been reached by Dr Hubble from the study of Cepheid variables discovered in the nebula. We have already explained the application of the method and it is necessary only to state the result. The Andromeda nebula is at a distance of 900,000 light-years. In a similar way, Dr Hubble found that the spiral nebula M. 33 was also at approximately the above distance from us. Knowing the angular dimensions of the great nebula in Andromeda, we can now calculate its dimensions in light-years. It is thus found that its diameter is about 50,000 light-years. The nebula's claim to be an independent stellar universe, organised on a grand scale and teeming with millions of stars, seems to be irrefutable. From its prominence in the sky—its greatest angular diameter is nearly 3°—it is more than probable that the Andromeda nebula is the nearest or one of the nearest of the spiral family. The apparently smaller spirals are probably at still more stupendous distances—perhaps 10 or 100 million light-years away. Who is there that can fail to be impressed with the sheer magnitude of the created universe?

In the southern skies, there are two conspicuous star clouds, quite remote from the Milky Way, called the Large Magellanic Cloud and the Small Magellanic Cloud. A photograph of the former is shown in Plate XX. These were first studied, with that skill and patience which had been lavished on objects visible in the observatories of the northern hemisphere, by Sir John Herschel during his memorable and fruitful stay at the Cape between 1834 and 1838. In both clouds, Herschel discovered a great number of star clusters and diffuse nebulæ which led him to believe that these great clouds must each be independent or island universes. Within more recent times, these objects have received and are still receiving a vast amount of attention. We have seen that it was for the Cepheid variable stars in the Small Cloud that the relation between luminosity and the period of light variation was first established. From more precise and extensive information, derived from an intensive photographic programme of observations, Dr H. Shapley has been able to assign what are believed to be reliable estimates of the distances of the two clouds. The Small Cloud

is at a distance of 100,000 light-years and the Large Cloud at a distance of 110,000 light-years. The diameter of the Small Cloud proves to be about 6500 light-years, and of the Large Cloud about twice this value. The Magellanic Clouds are thus island universes but on a much smaller scale than the great nebula in Andromeda. Spectroscopic observations show that the diffuse nebulæ belonging to the Great Cloud have an average velocity of recession of 170 miles per second; this velocity may be regarded as approximately the velocity of recession of the Large Cloud from the stellar system. At these great distances, the stars that can actually be photographed must represent only a small fraction of the total number of stars in the clouds. If there are stars in the Magellanic Clouds similar in every respect to our own sun, their apparent magnitudes must be about 23, which is a much fainter magnitude that can be reached even with our great telescopes. Modern photography, despite its tremendous power, can only show us the giant stars in the remote systems; up to the present, the dwarf stars have successfully evaded our most penetrating inquisition.



The Great Nebula in *Andromeda*.
*Yerkes Observatory of the University of Chicago.*

## CHAPTER XVII

### THE UNIVERSE

In the previous pages we have described the various classes of astronomical bodies—the sun and the members of the solar system, the stars, the dark and luminous nebulæ, the globular clusters and the spiral nebulæ. In this final chapter we shall attempt to present a picture of the universe in its most general aspects, and to refer to the possible origin and development of certain objects and systems whose very existence provokes the deepest interest and the fullest inquiry. Despite the almost unbelievable progress in all departments of the science and the illuminating assistance of present-day physics, modern astronomy is hardly presumptuous enough to declare that the secrets of the universe have been penetrated to any great depth. The citadel, indeed, is being attacked on all sides more furiously every day with all kinds of weapons, old and new, but all that the besiegers may be said to have gained is a distant and rather uncertain glimpse of the treasures of scientific truth within the walls. As in military affairs caution may be as essential as boldness, so in our contemplation of the universe we must combine our appreciation of even the boldest hypotheses with the reserve born of our experiences of the imperfection of human reasoning.

According to our present views, the universe is a vast assemblage of separate systems, each of great dimensions, which, however, are small in comparison with the stupendous distances by which any two neighbouring systems are separated from one another. We may liken the universe to a broad ocean studded with small islands of varying sizes ; one of the largest of these islands is believed to represent the system of which the solar system is but a humble member, the *galactic system*, as it is called. The other systems are the spiral nebulæ whose number we can but vaguely guess. We consider first the galactic

system in which the sun is situated. By the direct method of measurement, it is only possible to make a survey of that part of the galactic system within a few hundred parsecs of the sun. How can we gain a sufficiently reliable idea of the dimensions and form of our system? Sir William Herschel was the first to introduce into the problem a new method of attack which has been greatly developed within recent years. Briefly, the method is the apparently simple one of counting the number of stars of different magnitudes in various parts of the sky. It is well known to anyone who has looked through a telescope that the stars are most numerous in the Milky Way and very much less numerous at its poles. The Milky Way is roughly a great circle on the celestial sphere and it is a plane of symmetry, so that the distribution of stars on one side of it is fairly well reproduced on the other side. A complete investigation of the numbers of stars of different magnitudes in all parts of the sky is manifestly a task that would require more years and more labour than all the observatories in the world would feel justified in devoting to such a problem. In practice, then, the method is applied to certain regions of the sky selected according to their positions in relation to the Milky Way, and from the counts of stars in these regions, the distribution of stars all over the sky can be fairly accurately inferred. Let us consider firstly the numbers of stars of different magnitude scattered all over the sky. The following table, due to Dr Seares and Dr van Rhijn, gives the numbers of the stars brighter than the visual magnitudes 4·0, 5·0, . . . 20·0.

NUMBER OF STARS BRIGHTER THAN GIVEN VISUAL MAGNITUDES

| Visual Magnitude. | Total No. of Stars. | Ratio. | Visual Magnitude. | Total No. of Stars. | Ratio. |
|---|---|---|---|---|---|
| 4 | 530 | 3·1 | 12 | 2,270,000 | 2·5 |
| 5 | 1,620 | 3·0 | 13 | 5,700,000 | 2·4 |
| 6 | 4,850 | 3·0 | 14 | 13,800,000 | 2·3 |
| 7 | 14,300 | 2·9 | 15 | 32,000,000 | 2·2 |
| 8 | 41,000 | 2·8 | 16 | 71,000,000 | 2·1 |
| 9 | 117,000 | 2·8 | 17 | 150,000,000 | 2·0 |
| 10 | 324,000 | 2·7 | 18 | 296,000,000 | 1·9 |
| 11 | 870,000 | 2·6 | 19 | 560,000,000 | 1·7 |
| 12 | 2,270,000 | | 20 | 1,000,000,000 | |

The Greater Magellanic Cloud.
*Union Observatory, Johannesburg.*

It may be mentioned here that these results are based on the measurements of photographic magnitudes in the regions of the sky selected for this investigation; a suitable correction has been applied (depending on the average colour-index of the stars) to convert the photographic magnitudes into visual magnitudes. In the column headed "Ratio" are the numbers representing the ratio of the total number of stars brighter than a certain magnitude to the total number of stars brighter than the preceding magnitude of the table; thus the total number of stars brighter than magnitude 6·0 (this is the number of stars in the whole sky just visible to the naked eye) is just three times the number of stars brighter than magnitude 5·0. The striking feature of this table is the steady decrease in the values of the "ratio," from 3·1 for the bright stars to 1·7 for the very faint stars. Even the largest telescopes cannot push this inquiry to stars much fainter than the 20th magnitude, but if the decrease in the value of the "ratio" is continued in the same way then somewhere about magnitude 30 it may be inferred that the ratio will eventually become 1. This means simply that the total number of stars brighter than magnitude 30 is the same as the total number of stars brighter than magnitude 29; in other words, the magnitude sequence comes essentially to an end and we have reached the confines of the stellar system. Let us consider a little more particularly what the table shows us. Suppose for a moment that all the stars are alike, so that the visual magnitude is a true index of a star's distance from us. We recall that under these circumstances a star of magnitude 12 will be ten times further off than a star of magnitude 7. If we suppose that the stars are equally distributed in space, then it can be shown that, for example, the total number of stars brighter than magnitude 12 should be almost exactly four times the total number of stars brighter than magnitude 11. Thus if our suppositions hold for the stars of the galactic system, the values of the "ratio" in the previous table all ought to be 4. But as we know, the stars are not all alike—some are brilliant giants, some are feeble dwarfs, and the remainder are, in brilliancy, between these two extremes. If, however, we make the more reasonable assumption that any two volumes of space contain very much the same proportions of giants and

of dwarfs, the result is unaltered, namely, that the values of the "ratio" ought to be 4·0. The "ratio," as we have seen in the table, is a diminishing ratio; this must mean that the stars are not uniformly distributed in space but that there is a gradual thinning out as we go to greater distances. The galactic system must then be limited in extent, although it is hardly likely that there is a sharp boundary beyond which galactic stars cease to be found. There is one point that must be discussed somewhat briefly. The previous argument takes no account of the possibility that the light of a star, however distant, is unimpeded in its journey through space by material bodies or particles. In the Milky Way regions, there are vast obscuring clouds which conceal the stars behind; in the regions selected for the star-counts, these dark nebulæ have been carefully avoided. But may not the apparently waste regions of the galactic system contain myriads of independent particles, a gas or cloud of dust with a scattering power similar to that of our own atmosphere on the rays from the setting sun? In the latter instance, we attribute the redness of the sun at setting to the scattering of the short wave-lengths of sunlight by our atmosphere; the effect is essentially the abstraction of the blue light, leaving the red wave-lengths to represent the radiation that eventually reaches us from the sun. The light of a distant star would be similarly enfeebled if the light had to pass through a dust cloud, however fine; the star would, in fact, appear redder than it would appear if there was no scattering of its light. This point has been examined very carefully by Dr Shapley. The distant globular clusters contain stars of very much the same spectral classes as are found amongst the near stars; in particular, there are B class stars (blue in colour), the existence of which indicates almost certainly that if there is any scattering, it must be quite inappreciable in magnitude. The conclusion to which we are led is that the deduction made from the study of the previous table of star-counts remains substantially unaltered.

Let us now consider the distribution of stars in different galactic latitudes (on the celestial sphere we regard the Milky Way as a fundamental plane in a similar way to that in which we regard the earth's equator). The following table shows the average number of stars, brighter than various photographic

magnitudes, in areas of the sky 1° by 1° (about $4\frac{1}{2}$ times the area covered by the full moon) in galactic latitudes 0°, 45°, and 90°—the first refers to the Milky Way itself, the third to the poles of the Milky Way.

| Magnitude. (Photographic) | Galactic Latitude. | | |
|---|---|---|---|
| | 0° | 45° | 90° |
| 9 | 2·8 | 1·0 | 0·7 |
| 11 | 21 | 6·8 | 4·3 |
| 13 | 146 | 39 | 21 |
| 15 | 910 | 177 | 87 |
| 17 | 4,780 | 647 | 288 |
| 19 | 20,750 | 1,860 | 770 |
| 21 | 73,600 | 4,225 | 1,670 |

The table shows very clearly the marked differences in the density of the stellar population in the three galactic latitudes

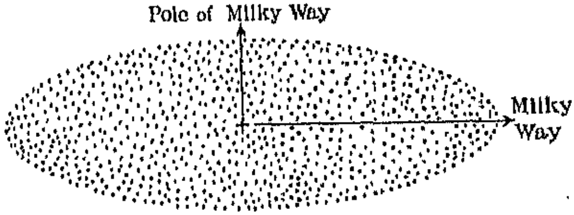



FIG. 102.

considered. It shows more; the thinning out of the stars towards the galactic poles is very much more rapid than the thinning out in the Milky Way itself. The inference is that the galactic system has a very much greater extension in the plane of the Milky Way than at right angles to this plane. The galactic system is thus conceived as a vast aggregation of stars shaped very much like a lens. If we assume for the moment that the sun is situated somewhere near the centre of the lens, then when we view the galactic system in the direction of the rim of the lens we are looking in the direction of the Milky Way where the stars appear most numerous. Looking towards either pole of the Milky Way we see fewer stars on account of the smaller depth of the galactic system in this direction and of the more rapid thinning out of the stars. Figure 102 is

intended to represent a section of the galactic system at right angles to the plane of the Milky Way.

The plane of the Milky Way is something more than the central plane of the galactic system; it is also the plane towards which certain objects show a remarkable concentration. The dark obscuring clouds, the bright diffuse nebulæ, the planetary nebulæ, novæ, and the open clusters are all found in or near this plane. The stars of spectral class B form a kind of flattened cluster with its central plane almost parallel to that of the Milky Way. Stars of class O—the hottest stars of all—are also markedly concentrated towards this plane.

We have seen that from his studies of the globular clusters Shapley has been able to calculate their distances. It is noteworthy that the great majority of the clusters are found in one hemisphere only of the sky and that they are fairly equally distributed on either side of the plane of the Milky Way. The nature of the distribution of the clusters suggests that the sun is at a great distance from the centre of the system formed by the clusters. Are we to regard the clusters as part of the galactic system or as dense aggregations of stars outside its limits? Shapley's view is that the clusters form, as it were, a series of boundary stones delimiting the galactic system from extra-galactic space, and thereby providing the means of estimating the dimensions of the galactic system itself. In this way the galactic system is pictured as an immense flattened lens-shaped system, its greatest diameter being 300,000 light-years in extent and its thickness 10,000 light-years. The sun is by no means near the centre of this vast system—it is believed to be 60,000 light-years distant from the centre, the direction of the centre as seen from the sun being towards the constellation Sagittarius. This conception of the galactic system raises the latter to a commanding position in the universe; so far as we know, the other great systems, the spiral nebulæ, cannot rival the galactic system in sheer immensity. Vast as undoubtedly their dimensions are, the spirals are but as islands in the universe; the galactic system has the dignity of a continent. It is well-nigh impossible to grasp the immensity of our galactic system and its isolation from the other great systems which, together with it, form the universe. We have said that the sun's speed relatively to the surrounding stars is 20 kilometres (or

12½ miles) per second. This is a stupendous speed without doubt, but even so, the sun would require 4500 million years to traverse, with this constant speed, the greatest diameter of the galactic system and quite three times this interval to reach the nearest spiral mebula.

The galactic system, it is safe to say, is a growing system, for its vast gravitational attraction will sweep within it any stray stars or groups of stars that come within its influence. Many of the globular clusters have high velocities of approach which will in due course bring some of these groups at least within the confines of the galactic system. Indeed, Dr Shapley has suggested that the open clusters, several hundreds in number, are all that remain of originally compact globular clusters that have suffered disruption in their passage through the greater galactic system. Nor is it easy for a star to escape from this mighty system. It is possible to calculate, for example, the speed at which a projectile must be fired to escape from the earth's control, but no gun yet invented has come within measurable distance of the achievement of such a feat. If we know the numbers, masses and distribution of the stars of the galactic system, we could calculate what a star's speed must be if it stands a chance of escape from the system. We do not know the data of the problem very accurately, but it is reasonably certain that "the velocity of escape" is very much greater than the known velocities of the vast majority of the stars. There are certain stars of high velocity, studied in recent years by Dr Oort and Dr Strömberg, which very possibly are but fleeting visitors; their speeds are so great that perhaps not even the immense gravitational attraction of the galactic system will be sufficient to keep them in subjection to its controlling sway.

The spectroscope has succeeded in measuring the rotation of some of the brighter spiral nebulæ; this immediately suggests the possibility that our own galactic system is also rotating. The matter can be tested by means of proper motions or of radial velocities. By the former, Professor Charlier arrived at the conclusion that the galactic system was actually rotating in a period not far short of 100 million years. But the proper motion data are perhaps not so reliable as a difficult investigation of this kind requires. Dr Oort has attacked the problem by

utilising the radial velocities. We have to distinguish between two possibilities: either the galactic system is rotating like a grindstone about its axis, or the motion of the stars is analogous rather to the revolution of the planets around the sun. The former alternative would mean that the average of the radial velocities of stars in different directions of the Milky Way would be much the same; this hypothesis of course can be easily submitted to the test. Let us consider the second alternative in greater detail. The sun, it is believed, is at some considerable distance from the centre of the galactic system; it is therefore under the gravitational sway of an immense number of stars whose mass we may suppose concentrated at the centre of the galactic system. For simplicity suppose further that the sun and stars are describing circular orbits around the centre. Then, as in the solar system, the nearer a star is to the

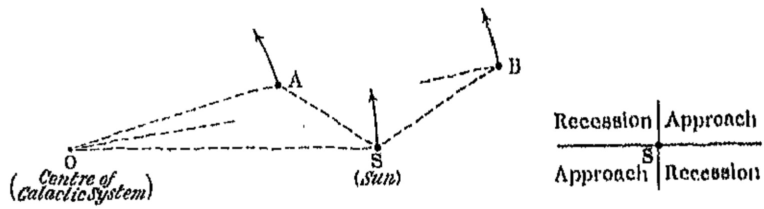



FIG. 103.

centre the greater will be its orbital speed. Consider two stars A and B, one nearer the centre O than the sun, the other more remote (Figure 103). The velocity of A at right angles to OA is greater than the velocity of S at right angles to OS. It is clear from the diagram that A is increasing its distance from S; this means that the radial velocity of A as measured in the usual way will be one of recession. Consider now the star B; its velocity at right angles to OB is less than the velocity of S at right angles to OS, and it is evident that the distance between B and S is diminishing; the radial velocity of B will then be one of approach. If the hypothesis which we have described has at least elements of truth in it, it is evident that the Milky Way can be divided into four quadrants in which the radial velocities of the stars are, on the average, velocities of approach and of recession in successive quarters as illustrated in Figure 103. Also, it should be added, it is the stars at great distances

from the sun that will demonstrate most forcibly the effect described. These are the ideas underlying Dr Oort's investigations, amplified more recently by Dr Plaskett at Victoria, B.C. Let us look at the results. One of the unknown factors in the problem is the direction, from the sun, of the centre of the galactic system; both Oort and Plaskett agree in locating the centre in a certain direction towards the constellation of Sagittarius. Now this direction is precisely that found by Dr Shapley from his study of the distribution of the globular clusters which, as we have seen, appear to outline the galactic system. This is a point in favour of Oort's theory. A second is even more remarkable. If the distance of the centre of the galactic system from the sun is known, it is possible from the theory to calculate the average velocity (of revolution) of stars near the sun; with Shapley's estimate of this distance, the velocity comes out to be about 190 miles per second. Now this is very nearly the average velocity of the globular clusters relatively to the sun or, expressed differently, this is practically the velocity of the stars near the sun with respect to the family of globular clusters regarded as a group. This may be illustrated in Figure 104, in which the flattened galactic system is represented, with exterior dots representing the globular clusters. Referred to the globular clusters the motion of the sun is 170 miles per second along SA, which is found to be almost exactly at right angles to the direction SC of the centre of the galactic system. This is practically the same result found by Oort, and thus furnishes confirmatory evidence concerning his theory. It is perhaps too soon to regard all the details of the theory as definitely established; its general outline appears, however, to have recommendations which cannot be lightly discarded. But it must not be imagined that it is anything but a generalisation.

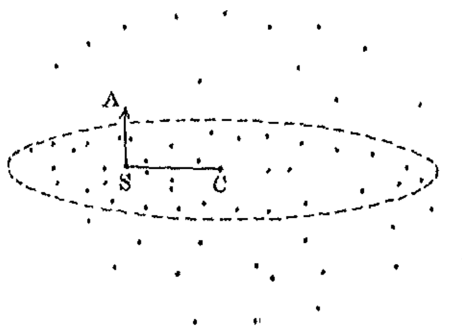


FIG. 104.

The galactic system is a very complex system—it contains all kinds of stars, the open and globular clusters, the diffuse and planetary nebulæ—and it is hardly reasonable to suppose that all these diverse objects or groups of objects have lost completely their independence as separate sub-systems. Moreover, the phenomenon of star-streaming cannot be explained in terms of such a general hypothesis as that of Oort. The conception of sub-systems, however, does afford an explanation; the motion of a local cluster of stars surrounding the sun through another system of stars would produce the characteristics of the phenomenon. We are still on the threshold of our inquiry into the architecture of, and the movements within, the great galactic system. We believe that we have some inklings as to the broad generalities of the plan, but the details are still obscure and beyond our ken.

What are the origins of the great systems of the universe of which the galactic system is but one? What is the raw material out of which stars are made, and what are the governing processes which assemble them into the great systems? These are questions that fascinate and stir the imagination, that cry out for an answer, however feeble and uncertain that answer may be. It cannot be pretended that this great mystery of the birth of worlds has been unlocked almost at the first attempt; many links in the chain of reasoning are hardly strong enough to bear the weight of criticism and some results of observation are open to question. Nevertheless, the picture of the birth of stars and systems which Sir J. H. Jeans has drawn is one of imposing grandeur. In the succeeding pages, we shall attempt to describe the conclusions of Jeans in the realm of cosmogony. The cosmogonist starts from a diffuse nebula as the raw material out of which stars and systems are eventually formed. Gravitation draws the particles of which the nebula is composed closer and closer together, eventually making it assume a comparatively compact form. But the cosmogonist requires more than a diffuse nebula and the law of gravitation; he requires, as a *sine qua non*, that rotation has in some way been started—rotation, in fact, is almost as necessary to the theorist as the nebula itself. A nebula without rotation would assume a spherical form, contracting under the influence of gravitation, but such a nebula would be hardly likely to become the parent of a multitude of

stars. If it be once granted that the primitive nebula has acquired a rotation, its subsequent progress can be followed. The effect of rotation is first of all to cause the nebula to be flattened, just as the earth is flattened towards its poles. But gravitation is continually drawing the particles ever closer together; by dynamical principles it follows that the greater the contraction the faster becomes the rotation. With increase in the rotation there is an accompanying increase in the degree of flattening until the form of the nebula is like a thin lens. Nebulæ of this form are known—*e.g.*, N.G.C. 4594 (Plate XVIII)—and in several instances the rotation has been measured; according to Jeans, such nebulæ are in the stage antecedent to the spiral form. Further shrinkage involves the break up of the nebula; this occurs as the ejection of matter from the equator of the lens-shaped figure of the

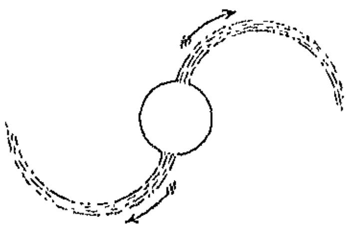


Fig. 105.

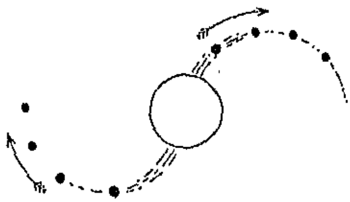


Fig. 106.

nebula. At this point in the rotational and gravitational development of the nebula, external forces are introduced as effective factors in the problem. No nebula is entirely remote from other masses; these masses exert their gravitational power on the rotating nebula, raising gaseous tides analgous to the tides produced by the sun and moon on the waters of our globe. The escape of the nebular material now takes place not at every point of the equator but at the two opposite points of "high tide"; the gas is ejected in the form of two filaments which owing to the rotation of the nebula assume the forms represented in Figure 105. Now the gaseous content of a filament is imagined so enormous that the gravitational attraction of any portion of it is sufficient to prevent the constituent gas from escaping into space. The result of gravitation is then the condensation of the filament at various points as illustrated in Figure 106. According to

the calculations of Jeans, these condensations have masses typical of the stars.

In this way, owing to rotation and the tidal effects of external bodies, the original nebula is conceived to develop into a spiral nebula which later becomes the parent of a stellar system, the newly-born stars moving outwards along the spiral arms. Can this conclusion be submitted to an observational test? The comparison of two plates of a spiral nebula such as M. 51 (Plate XVIII (*a*)) taken at a sufficient interval apart might be expected, if the velocities of the condensations are large enough, to show measurable proper motions along the spiral arms. Dr van Maanen at Mt. Wilson has made such investigations of several spiral nebulæ. His results are, generally, that the condensations are moving in the way indicated with a proper motion of about 2″ per century. If we know the distance of a nebula, we can then convert this angular motion into so many miles per second. Hubble, as we have seen, has succeeded in measuring the distance of the Andromeda nebula and also of the spiral nebula M. 33 by means of the Cepheid variables in these systems. The distance of M. 33 together with van Maanen's measures of the proper motions combine to indicate that the condensations are moving outwards along the spiral arms with a velocity of 16,000 miles per second. Dr Lundmark has also measured the proper motions on the same plates of M. 33 —his results are very much smaller, and with Hubble's estimate of the distance of this nebula they give an outward velocity of about 1500 miles per second. The very great discordance between the results of two experienced astronomers is undoubtedly due to the immense difficulty in measuring the hazy images of the condensations on the photographic plates. But even the less extravagant results of Lundmark are not easy to accept—for this reason. As has been already remarked, the rotational velocities of several spiral and elliptical nebulæ have been measured with the spectroscope. For example, at a point about half-way from the centre of N.G.C. 4594 (Plate XVIII) the velocity is 200 miles per second, truly an amazing speed; for points at some distance from the centre of the Andromeda nebula, the velocity is very much less, about 45 miles per second. If these velocities are

characteristic of the spiral nebulæ as a class, there are clearly two lines of explanation to account for the manifest discordance between the implication of van Maanen's measures and the magnitude of the radial velocities actually measured. Either van Maanen's proper motions are fictitious in the sense that they are very many times too large or else the estimates of the distances of the nebulæ are erroneous. The latter alternative involves the accuracy of the period-luminosity law for Cepheid variables, but the concensus of contemporary astronomical opinion is against throwing the blame in this direction. The discordance can only be cleared up in the future when a sufficiently long interval has elapsed to allow the attainment of much greater accuracy in the proper motions. In this respect Jeans' evolutionary theory of the birth of stars in the arms of the spiral nebulæ awaits observational confirmation. The significant fact, however, remains that in

(a) (b) (c)

Fig. 107.

the universe there are all three types of nebulæ, from the elliptical variety to the well-developed spiral type, which thus appear to afford support to the evolutionary processes described.

It might be expected that a similar explanation would account for the formation of the planets of the solar system from a rotating and diffuse nebula with the mass of the sun. But the two problems are dissimilar, for in the case of the incipient spiral nebula, the filaments are of such great size and mass that gravitation causes the condensation of the gaseous material, thus controlling the expanding tendency of the latter, whereas in a nebula of stellar mass, gravitation is powerless to prevent the dissipation of the filaments. The sequence of events in the latter case is believed to be as follows. The contraction of the rotating nebula is accompanied, as before, by increased rotation; if the rotation becomes very great, the star is unable to maintain itself as a distinct unit; it tends to break-up, eventually becoming a binary system. Figure 107

illustrates the sequence of changes involved in the "fission-theory," as it is called. According to Jeans, the fission of a star will occur when contraction has proceeded so far that the density of the stellar material is about one-tenth that of water. As we have seen in an earlier chapter, this is about the density of the B type stars. Not all stars, however, are capable of fission, for a sufficiently great rotation is necessary for the process; our sun, for example, is rotating much too slowly to be able to divide in the manner indicated. The large proportion of binary stars in the sky seems to indicate that it is a comparatively common experience for stars to acquire, in time, the critical rotation demanded by the theory. When once a binary star has been formed, each star produces on the other tidal effects which result in the separation of the two stars up to a calculable limit. The close spectroscopic binaries are thus believed to be comparatively young systems not far removed in time from the date of fission; the more open spectroscopic binaries are similarly regarded as systems of much longer standing. The tidal interactions of the components of a binary are, however, unable to produce the much greater separation of the components observed in the visual binaries. If the spectroscopic binaries evolve into visual binaries, some other agency must be invoked. Such an agency is provided by the dissipation of the stellar masses in the form of light and heat. But if this process is to be of any avail in this connection, Jeans' drastic hypothesis of the annihilation of matter within the star, or some similar hypothesis, must be brought into the problem. Let us consider a particular example of a spectroscopic binary with components thirty and three times respectively more massive than the sun; let us suppose, further, that the period is 10 days. It should be added that these assumptions are not inconsistent with our knowledge of the binary systems. After 7 million million years, the masses will be almost exactly equal to the solar mass—the calculations are based on the theory of the loss of mass due, for example, to the annihilation of matter within the stars—and the period of the binary will then be about 100 years. The separation of the components and the period will now have the characteristics of a visual binary star. With the assumptions made, the theory appears adequate to explain the evolution of a massive spectroscopic binary into a visual binary of the

comparatively short period of 100 years. But if we seek to explain in this way the formation of visual binaries with periods of several hundreds of years we are faced with a difficulty, for it will be necessary to assign to the components of the original spectroscopic binary masses very much greater than have hitherto been observed. It seems very probable that the vast majority of visual binaries have evolved throughout the long cosmogonic ages from the close spectroscopic binary system, but the complete explanation of the process is still to be found.

In many ways, the most interesting problem in the life of the universe is the formation of our solar system. In the first chapter of the book we briefly indicated the uniform characteristics of the planets and satellites—the eight great planets revolve in the same direction around the sun in almost the same plane; with a few exceptions, the satellites behave in a similar manner. This uniformity suggests that the bodies of the solar system have not been brought together at different times as the result of a series of accidental captures by the sun, but rather that the system as a whole is the consequence of one single cosmic phenomenon. We have not even the evidence of other similar systems in the universe to aid in unravelling the mystery of its origin. Viewed from the nearest star, our sun would appear as a star of about the first magnitude, and Jupiter, our greatest planet, would appear as a faint speck of light of about magnitude 22 at a distance of about 4 seconds of arc from the sun. Our greatest telescopes would thus be powerless to detect similar planetary systems (if such existed), belonging even to the nearest stars. So far as direct observation is concerned, we are unable to say whether the solar system is unique in the universe or not. But we have still to consider by what process the solar system could have been brought into existence in much its present form. The distance between one star and another is so great that tidal influences would be too minute to produce any marked change in the form of a star. But the stars are moving hither and thither in the galactic system with stupendous speeds, and the possibility of the near approach of a star to the sun in some far distant age must not be overlooked. In such an event, great tides would be raised on the sun which might very well provide the mechanism for the expulsion from the sun of masses of gas comparable in magnitude to the masses of the

planets. This in brief is the basis of Sir J. H. Jeans' theory of the origin of the solar system. We have seen in an earlier chapter that the earth must be considered at least two thousand million years of age; the birth of the planets must therefore have occurred at a very remote time when the sun was somewhat less condensed than it is at present.

The chief point in the theory is that the disturbing star must have approached the sun at a distance not much greater than the solar radius. Now, when we remember the dimensions of the stars and the vast distances by which they are separated, such an occurrence must be extremely uncommon. Imagine two swallows flying in any haphazard

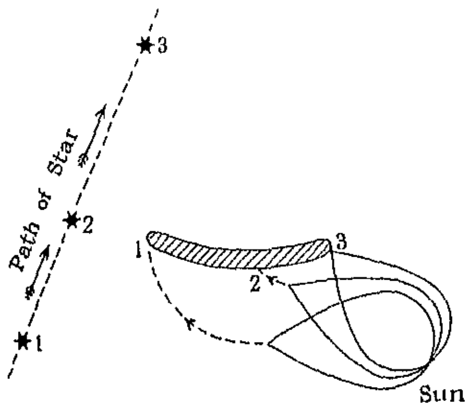



FIG. 108. (After H. Jeffreys.)

direction, one from England, the other from Australia; the chance that at some point in their respective tracks they will be within six inches of each other is just about equal to the chance of two stars making the very close approach contemplated in the theory. As the disturbing star approaches the sun, its tidal effects increase in magnitude so that eventually a great jet of the solar gases is ejected from the regions on the sun's surface corresponding to high-tide, and the ejection is supposed to continue so long as the visiting star is within effective distance of the sun. Figure 108 illustrates the changes in the form of the sun and the paths of portions of the ejected matter during the visit of the star. The gaseous material cools and contracts and forms different condensations at various

distances from the sun's centre; these condensations become the planets. In a similar way, tidal disruption is made to explain the origin of the satellite systems. For example, after the formation of Jupiter the sun or the passing star acts now as the disrupting tidal agency on the newly-born planet and the result is the system of satellites. In broad outline, this is Jeans' theory of the origin of the solar system. It does not pretend to account for every observed detail in the structure of the solar system—such as the origin of satellites with retrograde motions—but it may justly claim to give a very probable explanation of the birth of planets and satellites. It is of interest to notice that if the visiting star happened to be about as massive as the sun, the sun would produce similar tidal effects on the star; in other words, the sun and the star would both acquire a family of planets as a result of their mutual encounter.

According to the present distribution of stars in the galactic system, the probability of the close encounter of any two stars is extremely small, and it might be inferred at once that the solar system is almost unique in the universe. But the question has to be asked: is the present distribution of stars representative of the distribution several million million years ago? If the stars are annihilating their masses in the way Jeans has described, it follows that the galactic system must be steadily expanding, so that in the very remote past the stars must have been much more densely packed together than at present. The chance of close encounters is thereby greatly increased and the formation of planetary systems may have been rather more common. Returning to our analogy of the swallows, we may represent the probability as about equal to the chance of the two swallows, flying on a steady course in any haphazard direction, one from Edinburgh and the other from London, passing within six inches of each other. Against this, however, must be set the fact that the stellar population of the galactic system is very likely increasing, so that in the very remote past the number of the stars in the system may have been appreciably less than at present. In any event, the galactic system is, and has been in the past, unlikely to be productive of more than a few planetary systems such as our own. In the globular clusters and perhaps in the spiral nebulæ the much closer packing of the stars presents much more

favourable conditions for the tidal disruption of stars; it may be legitimate to speculate that in these vast aggregations of stars the existence of solar systems may not be quite as uncommon as in the galactic system.

As regards the origin of the earth's satellite, the moon, there are certain difficulties in believing that its birth took place according to the principles previously outlined for the other satellite systems; for one thing, the ratio of the moon's mass to that of the earth is about sixty times greater than the ratio of the mass of the greatest satellite (Titan) to the mass of its parent planet (Jupiter). The most plausible theory was advanced by Sir George Darwin. According to the theory, the moon was originally a part of the earth; from dynamical principles, it can be shown that the earth must then have rotated in a period of about four hours. When the earth was still wholly or partly in a liquid state, the tidal influence of the sun on the quickly rotating earth produced the fission of the parent body and so the moon was born; the mutual tidal effects of the liquid earth and the newly born liquid moon caused the gradual separation of the two bodies.

In the preceding pages we have outlined what are believed at the present time to be the cosmic processes silently at work in the formation of the great stellar systems, and the processes which in the remote past have resulted in the birth of the planetary and satellite systems. We turn now to a different subject of great interest. We have seen that in the galactic system the stars are at stupendous distances one from another; if we imagine a grain of sand situated at the centre of each of the English counties we obtain some kind of picture of the distribution of the stars in the galactic system. The question is immediately suggested: "Are the vast regions of inter-stellar space absolutely untenanted by matter in any shape or form?" We know, of course, that there are extensive obscuring nebulæ in different regions of the Milky Way consisting of matter in a highly rarefied condition, and it is more than likely that these dark nebulæ extend in a still more tenuous state to regions where their obscuring power can hardly be detected in the ordinary way. It is the regions of the stellar system where there are apparently no obscuring clouds that we propose now to consider. At first sight, it would seem that direct observation

could furnish little or no definite information concerning the vacuity or otherwise of interstellar space, but recently Dr Plaskett's observations of spectroscopic binaries of spectral class B have thrown light on the problem in a remarkable way. The binary character of these stars is of course revealed by the periodic changes in the positions of the spectrum lines; but in certain stars it is found that the H and K lines of calcium (and the lines of sodium) do not share in these cyclical changes and that, in fact, they are stationary in the spectrum. When both components of the binary produce lines in the spectrum, it is possible to calculate the radial velocity of the binary as a system towards or away from the sun; the measurement of the fixed calcium lines also leads to the radial velocity of the calcium which produces these lines. Plaskett found that in general the two velocities are different; clearly, the calcium cannot belong to the stars. Moreover, the radial velocities deduced from the fixed calcium lines for stars situated in different parts of the sky were such as could be attributed to the effect of the solar motion. The inference is that between us and these distant B type stars there is a rarefied cloud of calcium and sodium atoms. But the reader will remember that the H and K lines are produced by singly ionised calcium atoms; how comes it that in interstellar space the calcium atoms have lost an electron apiece? The answer is that even at great distances from the stars the intense stream of radiant energy is still able to disrupt the calcium atoms; once the electron has been ejected, there is very little risk of the smashed atom capturing a wandering electron, owing to the extreme tenuity of the cloud. More than that, it is more than likely that the vast majority of the calcium atoms are doubly ionised—the stationary absorption lines (H and K) are thus due to a very small fraction of the calcium atoms between us and the particular star concerned. Clearly, too, the fixed lines will vary in intensity according to the distances of the stars observed; the further off the star, the greater the number of ionised atoms in the path of the light emitted by the star in our direction. This conclusion has been put to an observational test by Mr Otto Struve, who finds general confirmation for stars up to a distance of about 1500 light-years from the sun. Beyond this distance, stellar parallaxes have little claim to be regarded as reliable, and there-

fore the test has a somewhat circumscribed application. The detection of the interstellar cloud must appeal to the reader as a very remarkable achievement, and more so when the tenuity of the cloud is considered. Professor Eddington has calculated that the density is one atom per cubic inch. To realise what this means, suppose that we calculate the number of atoms in the calcium cloud within a straight tube of one square inch cross-section extending from the earth to a distance one hundred times the distance of the nearest star; the number so found is roughly the number of atoms in a cubic inch of the air we breathe. When the facts are expressed in this way, space seems amazingly empty, but as Professor Eddington puts it—" Perhaps it is the fulness that impresses us most. The atom can find no real place of solitude within the system of the stars; wherever it goes it can nod to a colleague not more than an inch away."

Here we bring our survey to a close. It has been a story of man's ceaseless endeavour to unravel the mysteries of the created universe, and to grapple with the infinities of space and time. With the physicist, we have explored the infinitely small; with the astronomer, the infinitely great. We have been spectators of the stately drama of the evolution of worlds and on the wings of light we have sped over the oceans of time. It is a magnificent spectacle that modern astronomy has revealed to us; before it, we stand in awe and reverence.

# INDEX



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